SP↓NSW↑TCH Summer School
Spin torque transfer and domain wall dynamics
SP↓NDYNAM↑CS
14-18 September 2009, Iași (Romania)

Summer School Program
&
Book of Abstracts

Organized by the
National Institute of Research and Development of Technical Physics, Iași (Romania)
in the framework of the Marie Curie Research Training Network
"Spin Current Induced Ultrafast Switching" – SPINSWITCH
Contract No.: MRTN-CT-2006-035327
STEERING COMMITTEE

Horia CHIRIAC (Local Chairman)  
(National Institute of R&D for Technical Physics, Iasi, RO)

Burkard HILLEBRANDS  
(Technische Universität Kaiserslautern, DE)

Russell COWBURN  
(Imperial College London, UK)

Claude CHAPPERT  
(Université Paris - Sud XI, FR)

Bernard DIENY  
(Commissariat à l'Energie Atomique (CEA), Grenoble, FR)

Mathias KLÄUI  
(Universität Konstanz, DE)

Mauricio MANFRINI  
(IMEC, Leuven, BE)

PARTNERS

Summer School Secretariat

SPINDYNAMIS Summer School  
National Institute of Research and Development for Technical Physics  
47 Mangeron Blvd., RO-700050 Iasi, Romania  
Phone: +40 232 430680 / Fax: +40 232 231132 / E-mail: spindynamics@phys-iasi.ro  
http://www.phys-iasi.ro/spindynamics/  
http://www.spinswitch.de  
http://www.spinswitch.eu
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<td>Alexandru STANCU</td>
<td>Magnetic Logic (I)</td>
<td>Jacques-Olivier KLEIN</td>
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<td>Shinji YUASA</td>
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<td>Magnetic Logic (I)</td>
<td>Jacques-Olivier KLEIN</td>
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<td>Yoshichika OTANI</td>
<td>Magnetic Logic (II)</td>
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<td>12:30 – 13:00</td>
<td>Ursula EBELS</td>
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<td>Tomasz STOBIECKI</td>
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<td>Jean-Claude MAGE</td>
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<td>9:00 – 11:00</td>
<td>Morning Session I / Chair: Horia CHIRIAC</td>
<td>Burkard HILLEBRANDS</td>
<td>Faculty of Physics, Technical University of Kaiserslautern, Kaiserslautern, Germany</td>
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<td>11:30 – 12:30</td>
<td>Morning Session II / Chair: Guillaume PRENAT</td>
<td>Alexandru STANCU</td>
<td>“Alexandru Ioan Cuza” University, Department of Physics, Iasi, Romania</td>
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<td>STATIC AND DYNAMIC INTERACTIONS IN NANOPARTICULATE MAGNETIC MEDIA</td>
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<td>Ursula EBELS</td>
<td>SPINTEC, CEA, CNRS, UJF, INPG, CEA/INAC, Grenoble, France</td>
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<td>Afternoon Session / Chair: Jacques-Olivier KLEIN</td>
<td>Tomasz STOBIECKI</td>
<td>AGH University of Science and Technology, Kraków, Poland</td>
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<td>EXCHANGE BIAS MAGNETIC TUNNEL JUNCTIONS WITH MgO WEDGE BARRIER: MICROSTRUCTURE AND SPIN TRANSFER</td>
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<td>Moritz EGGELING</td>
<td>Austrian Institute of Technology GmbH – AIT, Division Nano Systems, Vienna, Austria</td>
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<td>SPIN TORQUE DOMAIN MANIPULATION IN EXCHANGE BIASED SPIN-VALVE NANOCONTACTS</td>
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<td>João SAMPAIO</td>
<td>Department of Physics, Blackett Laboratory, Imperial College London, United Kingdom</td>
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<td>LOGIC AND DATA STORAGE IN SPIN VALVE NANOWIRES</td>
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<td>9:00 – 11:00</td>
<td><strong>MAGNETIC LOGIC SESSION (I/1)</strong></td>
<td>Jacques-Olivier KLEIN</td>
<td>Institut d'Electronique Fondamentale, Université Paris-Sud, UMR 8622, Orsay, France</td>
<td>FROM TRENDS IN CMOS DIGITAL ARCHITECTURE TO MAGNETIC LOGIC OPPORTUNITIES</td>
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<td>BESIDES MRAM, CMOS/MTJ INTEGRATION FOR LOGIC COMPONENTS</td>
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<td>11:30 – 12:30</td>
<td><strong>MAGNETIC LOGIC SESSION (I/2)</strong></td>
<td>Jacques-Olivier KLEIN</td>
<td>IEF, Université Paris-Sud, UMR 8622, Orsay, France</td>
<td>FROM TRENDS IN CMOS DIGITAL ARCHITECTURE TO MAGNETIC LOGIC OPPORTUNITIES</td>
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<td>Institut d'Electronique Fondamentale, UMR CNRS 8622, Université Paris-Sud, Orsay, France</td>
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<td>SPIN TORQUE OSCILLATORS BASED ON VORTICES IN POINT CONTACTS</td>
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<td>Afternoon Session / Chair: Thibaut DEVOLDER</td>
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<td>Pavel BALAZ</td>
<td>“Adam Mickiewicz” University, Institute of Physics, Poznań, Poland</td>
<td>NONLINEAR MAGNETORESISTANCE IN DUAL SPIN VALVES: PHENOMENOLOGICAL MODEL</td>
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<td>15:30 – 16:00</td>
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<td>Mauricio MANFRINI</td>
<td>IMEC, Leuven, Belgium</td>
<td>SPIN-TORQUE OSCILLATIONS IN ZERO MAGNETIC FIELD</td>
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<td>16:00 – 16:30</td>
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<td>David AURELIO</td>
<td>Departamento de Fisica Aplicada, Universidad de Salamanca, Salamanca, Spain</td>
<td>THERMAL EFFECT ON SPIN-TORQUE-DRIVEN HIGH-TMR MAGNETIC TUNNEL JUNCTIONS</td>
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<td>Christoforos MOUTAFIS</td>
<td>Cavendish Laboratory, Cambridge, United Kingdom</td>
<td>DYNAMICAL PROCESSES FOR MAGNETIC BUBBLES IN NANOELEMENTS</td>
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| 9:00 – 11:00 | John Chapman  
*Department of Physics\&Astronomy, University of Glasgow, United Kingdom*  
**Domain Wall Behaviour in Magnetic Nanoelements and Wires** |
| 11:00 – 11:30 | **COFFEE BREAK** |
| 11:30 – 13:30 | Shinji Yuasa  
*National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, Japan*  
**Tunnel Magnetoresistance Effect in Magnetic Tunnel Junctions** |
| 13:30 – 14:30 | **LUNCH** |
| 14:30 – 20:00 | **SUMMER SCHOOL EXCURSION** |
| 20:00 – 22:00 | **SUMMER SCHOOL DINNER** |
**THURSDAY**  
September 17, 2009

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<tr>
<td>9:00 – 9:30</td>
<td>Mathias KLÄUI</td>
<td>ERC Research Group Nanomagnetism, Fachbereich Physik and Zukunftskolleg Universität Konstanz, Konstanz, Germany</td>
<td>CURRENT-INDUCED MAGNETIZATION DYNAMICS</td>
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<td>9:30 – 10:00</td>
<td>Luis LOPEZ-DIAZ</td>
<td>Universidad de Salamanca, Departamento de Fisica Aplicada, Salamanca, Spain</td>
<td>MODELLING SPIN TRANSFER INDUCED DYNAMICS; INTERPLAY BETWEEN MICROMAGNETICS AND OTHER SIMPLE MODELS</td>
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<td>10:00 – 10:30</td>
<td>Ricardo FERREIRA</td>
<td>Instituto de Sistemas e Nanotecnologias (INESC-MN), Lisbon, Portugal</td>
<td>COMPARISON BETWEEN A SELF-ALIGNED AND A CMP BASED NANO-PILLAR FABRICATION PROCESSES</td>
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<td>10:30 – 11:00</td>
<td>Vincent CROS</td>
<td>Unite Mixte de Physique CNRS/Thales and Université Paris Sud, Palaiseau, France</td>
<td>SPIN TRANSFER INDUCED VORTEX DYNAMICS IN MgO BASED MAGNETIC TUNNEL JUNCTIONS</td>
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<td>11:30 – 13:30</td>
<td>Yoshichika OTANI(^1,2)</td>
<td>ISSP, University of Tokyo, Chiba, Japan</td>
<td>SPIN CURRENTS AND NON-LOCAL DEVICES</td>
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<td>Russell COWBURN</td>
<td>Department of Physics, Blackett Laboratory, Imperial College London, United Kingdom</td>
<td>THE THINGS I WISH SOMEONE HAD TOLD ME BEFORE I STARTED A COMPANY</td>
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<tr>
<td>Time</td>
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<td><strong>Morning Session / Chair: Shinji YUASA</strong></td>
<td>Robert L. STAMPS, School of Physics, University of Western Australia, Perth, Australia</td>
<td>CONTROL OF MAGNETIZATION DYNAMICS USING PATTERNED STRUCTURES</td>
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<td><strong>MAGNETIC LOGIC SESSION (II)</strong></td>
<td>Russell COWBURN, Department of Physics, Blackett Laboratory, Imperial College London, United Kingdom</td>
<td>DOMAIN WALLS IN NANOWIRES FOR DIGITAL LOGIC AND MEMORY</td>
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<td>12:30 – 13:00</td>
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<td>Alexander SERHA, Fachbereich Physik and Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, Germany</td>
<td>SPIN WAVE LOGIC</td>
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MAGNETORESISTANCE AND CURRENT-INDUCED MAGNETIZATION REVERSAL OF SINGLE Py AND MULTILAYERED Py/Cu NANOWIRES
Spin waves are the dynamic excitations of the magnetization in a magnetically ordered solid state material. In my lecture I will give an introduction into the basic phenomena of spin wave propagation in magnetic materials and into fundamental experiments.

First, the physics of spin waves in the dipole and dipole-exchange regime including discussion of surface and backward volume spin waves is addressed. A particular focus will be set on the application to spin wave dynamics in small magnetic structures. The physics is illustrated by experimental results obtained by advanced Brillouin light scattering techniques, a powerful and versatile tool to investigate spin-wave properties. I will introduce into Brillouin light scattering spectroscopy and present space-, time- and phase resolving setups.

After discussing the spin-wave tunneling effect through magnetic barriers and mechanical gaps, I will present spin wave propagation phenomena in structures with inhomogeneous internal field distribution, in particular stripes and rings.

I will conclude by showing and discussing a wide variety of spin-wave phenomena in magnetic rings like propagation of spin waves, formations of several classes of spin-wave eigen-modes, localized spin waves, up to effects of spatial and temporal coherency and non-local dissipation by nonlinear mode coupling.
In order to assure improved technological parameters for many applications magnetic particles with smaller and smaller volumes are used. The packing ratio of these systems is also necessarily increased which gives higher densities of particles on the unit of surface or volume.

From the theoretical point of view strongly interacting magnetic nanoparticles are a quite difficult to model. It is well known that at a given temperature, below a certain critical volume, the ferromagnetic particles have a superparamagnetic behavior. In a particulate system usually the particles’ volumes are distributed and in an experiment performed at constant temperature some of the particles are blocked and the others have a superparamagnetic behavior. It is of paramount importance to understand profoundly the interactions between the blocked particles and between the superparamagnetic particles.

The interactions between the blocked particles have been studied for many years, mainly in the context of magnetic characterization of particulate recording media. Experimental methods like the Henkel plot, deltaM curve or, more recently First-order Reversal Curve (FORC) diagram method provides en evaluation of the interactions between hysteretic particles. Both physical (micromagnetic) and phenomenological models (mainly Preisach-type) can describe quite accurately the magnetization processes of systems of single domain ferromagnetic particles. Essentially in a particulate medium we have a distribution of interaction fields which is not completely stable. Both the mean value and the dispersion of the Interaction Field Distribution are dependent on the total magnetic moment of the sample.

When the total magnetic moment of the system is essentially influenced by the thermal effects, that is when the particles are superparamagnetic, the interaction can’t be described as a distribution of interaction fields. Experimental studies have shown that the interactions are producing an increase of the mean anisotropy of the particles. This type of interaction may be called dynamic interaction.

We shall present a Preisach-Néel model in which both static and dynamic interactions can be taken into account and magnetization dependence as a function of the applied field, time and temperature can be calculated.

**Recommended publications in this topic of the author**

Using spin polarized currents it is possible to drive the magnetization of a thin film magnetic element into large angle steady state oscillations. While of general interest for magnetization dynamics, these steady state oscillations combined with the magneto resistance effect are also of interest for integrated microwave component applications. These require addressing two major issues, which are the output power and the microwave emission linewidth. Due to the much larger magneto-resistance of magnetic tunnel junction devices of 50-100% as compared to spin valve devices (few percent), the output signal is considerably enhanced. This has been demonstrated in recent experiments by a number of groups. However, when using frequency domain analysis it is not always possible to clearly distinguish the steady state excitations from thermally excited spin wave modes. In this presentation we will show, that by investigating the oscillator output signal in the time domain this transition can be much better identified. This will be demonstrated for two ‘types’ of magnetic tunnel junction devices that differ in their magneto-resistance value and in their dynamic behaviour. Besides the transition from the sub-critical into the steady state regime, time domain studies also reveal important information on modes that seemingly appear simultaneously in frequency domain spectra. Finally, time domain analysis provides also some insight as to the origin of the free running oscillator linewidth.
EXCHANGE BIAS MAGNETIC TUNNEL JUNCTIONS WITH MgO WEDGE BARRIER: MICROSTRUCTURE AND SPIN TRANSFER TORQUE

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The purpose of our contribution is to optimize the sputtering conditions and the thickness of MgO tunnel barrier in exchange bias spin valve magnetic tunnel junctions (EB-SV MTJs) in order to obtain high tunneling magnetoresistance ratio (TMR) and low sheet resistance (RA resistance area product). We focused on the investigation of the influence of Ar partial pressure during the MgO deposition, to optimize TMR, structural and magnetic properties of MTJs with a low RA.

All films used in this study were deposited onto thermally oxidized Si (100) wafers in Timaris cluster tool system from Singulus Technologies. This system employs 10 cathodes in one deposition chamber and utilizes a linear dynamic deposition (LDD) technology. The stack of the investigated MTJs was substrate / seed layers / PtMn(16) / Co₀₇₀Fe₂₃₀(2.0) / Ru(0.9) / Co₄₀Fe₄₀B₂₀(2.3) / MgO wedge / Co₄₀Fe₄₀B₂₀(2.3) / cap layers (thickness in nanometers). In order to utilize current in plane tunneling (CIPT) measurements the seed and cap layers were: Ta(5) / CuN(50) / Ta(3) / CuN(50) / Ta(3) and Ta(10) / CuN(30) / Ru(7), respectively. MgO wedge layer was sputtered from sintered MgO target using LDD wedge technology. The Ar partial pressure was varied, from 1 mTorr up to 15 mTorr. After the deposition, MTJ films were annealed in a high-vacuum furnace at 360°C for 2 h in a magnetic field of 10 kOe.

The optimized conditions of low Ar pressure (from 1 mTorr to 3.8 mTorr) resulted in highly (001) oriented MgO barrier. Using this barrier we achieved TMR and RA values between 70% up to 160% and 1 Ohm µm² up to 3 Ohm µm², respectively. The junctions prepared in the high Ar pressures (above 3.8 mTorr) characterize, in comparison to low Ar pressure deposited junctions, with lower (001) MgO texture, higher amplitude of roughness, higher interlayer ferromagnetic coupling and lower values of TMR.

Spin transfer torque in nanopillars with RA product ranging from 1.8 Ohm µm² to 10 Ohm µm² and sizes of 0.13 µm² (280×620 nm²) down to 0.03 µm² (160×250 nm²) and TMR ratio reaching up to 170% was observed.

Spin polarization efficiency depends on a barrier thickness due to spin filter effect, therefore the critical current density was lower for 0.96 nm than for 0.71 nm of MgO thickness MTJs nanopillars.

Acknowledgements
The work in AGH Krakow: diffraction, CIMS, AFM and magnetic measurements was supported with research funding from the European Community under the FP6 – Marie Curie Research Training Network “SPINSWITCH” Contract Number MRTN-CT-2006-035327 SPINSWITCH.
J.W. would like to thank Singulus Technologies for the opportunity of MTJ stack deposition and CIPT characterization. W.S. would like to thank prof. Reiss group at Bielefeld University for the help with nanopillars fabrication process in the frame of his scholarship supported by the Foundation for Polish Science MPD Programme co-financed by the EU European Regional Development Fund.
In this work we will report on spin torque experiments on point contact devices patterned by a combination of UV and e-beam lithography on top of exchange biased spin valve multilayers. These were sputter-deposited and have the following structure (nm): Cu(25)/Mn$_{83}$Ir$_{17}$(15)/Co$_{70}$Fe$_{30}$(5)/Cu(7)/Co$_{70}$Fe$_{30}$(2)/Ni$_{80}$Fe$_{20}$(5)/Ta(2)/Au(3).

The magnetic properties of the spin valves were optimized for large exchange bias of the bottom hard electrode and minimum magnetostatic coupling. The magnetoresistance in the current perpendicular-to-plane geometry is measured approximately 0.2 %.

The dV/dI versus current measurements show pronounced, hysteretic peaks and dips, the relative amplitude and position of which are changing as a function of the in plane magnetic field. The latter is varied within the range of 40 to 70 Oe, in the vicinity of the coercive field of the element. These features appearing for both current polarities can be explained with a model that takes into account the spin transfer torque, as well as the interlayer exchange and magnetostatic coupling interacting in the detection layer.

(1) Minor magnetoresistance loop from circular contact of about 90-110 nm in diameter. (2) Output of lock-in amplifier as a function of the current. The current is swept from 0 to +15 to -15 to 0 mA. Positive current corresponds to electron flow from the fixed to the detection layer.
Domain walls (DWs) in magnetic nanowires are the basis for several proposed logic and data storage devices [1,2]. One proposed device [3] uses external magnetic fields and the shape of the nanowire to realise a data storage device using DW logic NOT gates as a memory element (Fig. 1). Prototypes for this [4] and other proposed DW devices have been realised using the magneto-optical Kerr effect or the small amplitude anisotropic magnetoresistance, both unif for practical devices. In the current work, we describe the integration in a Spin-Valve (SV) stack of the nanowire and associated logic structures, demonstrating the fully-electrical read-out of such DW memory element. We have fabricated SV nanowires with a Py free layer using e-beam lithography and ion milling. Gold contacts were patterned by lift-off. Electrical measurements showed a magneto-resistive signal comparable to the bulk SV (2% vs. 3%). No loss was observed in the magneto-resistive signal with nanowire width (200 to 30nm). We also observed a good distinction between the fields necessary for DW nucleation and propagation (200 vs. 25 Oe), making these excellent DW conduits, which is essential for data consistency. This was observed even in the narrowest wire, 30nm wide (500 vs. 110 Oe). We then fabricated straight and ring wires 100nm wide with a NOT-gate memory element. Electrical measurements showed that the element behaved as a NOT gate, as the DW inverted from head-to-head to tail-to-tail. Furthermore, we also demonstrated the operation of a high efficiency DW gate in SV nanowires, also previously studied in Py [5]. We observed that in SVs with a synthetic antiferromagnet reference layer the range of fields in which the structure correctly operates is similar to that obtained for Py structures. This shows that the used SV layers have a negligible influence on the device and lead us to believe that more complex systems can be integrated into optimised high-signal SVs for future practical devices.

![Fig 1. a) SEM image of SV ring wire with NOT gate before contact deposition. The stars indicate where the gold contacts were patterned. Inset: magnetic configuration of the NOT gate before and after DW passage. b) Measured MR signal (red straight line) and x-component of the rotating external field (blue dashed line). The magnetisation reverses every 3/2 cycles due to the NOT gate action [3].](image)

**References**

FROM TRENDS IN CMOS DIGITAL ARCHITECTURE TO MAGNETIC LOGIC OPPORTUNITIES

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Today’s digital architectures are uniquely build from MOSFET which appeared to be the ideal component during the last decades while the scaling of this technology benefited to density, power consumption, and speed. Nowadays, the race for scaling transistors to ultimate dimensions stays of current events to increase the functional density, but the benefits on speed and power consumption vanished. This is mainly due to the difficult trade-off between the impact of the MOSFET threshold voltage on speed and power consumption. As the impact of static power dissipation become preeminent and the total power dissipation reaches its limits, increasing the frequency of CPU is no more feasible. Consequently, multicore architectures constitute now the only solution to continue to increase the performances of processors. The gain in the performance / power ratio is notably due to the use of relatively slow MOSFET (with low VT) which feature low leakage current and low static power consumption. System designers search new techniques to reduce power consumption, like clock gating or asynchronous communication protocols to reduce the consumption of unused blocks, and notably the one associated to the clock signal distribution tree, but the possibility to completely turn off the power supply of logic blocks or CPU cores in stand by mode may be the ultimate solution to reduce standby static power consumption. In this context, magnetic logic can first brings its inherent non-volatility to mixed CMOS / magnetic circuits. The design of such circuits mixing MTJ and CMOS to increase their reliability and minimize their consumption using dynamic logic techniques is an active research topic. The same non-volatile flip-flop can be used to design programmable circuit (FPGA), not only to define the logic functions (LUT and interconnect) but also to sample periodically the global state of the circuit so it can be instantaneously restarted. In addition, more innovative architectures where magnetic components are used to build logic functions are studied. Threshold logic [1] and domain wall logic [2] are often quoted as possible solutions, but as we will see, the demonstration of basic Boolean functions [1,2,3] (like AND, OR, NAND, NOR) is not sufficient: others intrinsic features of CMOS logics like cascadability with direct propagation of logic signal in combinatorial gates are also required to mimic the CMOS digital design methods [4]. Otherwise, design strategies must be adapted to reach globally the same functionality than CMOS digital circuits. This will be illustrated with synthesize of a Magnetic Domain Wall Logic based Finite State Machine [5].

References
The general purpose of spin-electronics is to take advantage of the spin of the electrons in addition to their electrical charge to conceive innovative electronic devices. Magnetic Tunnel Junctions (MTJ) are key basic elements in these devices. As non-volatile variable resistors, they can be combined with standard CMOS components for the design of Magnetic Random Access Memories (MRAM), Magnetic Field Programmable Gate Arrays (M-FPGA), low-power ASICs (Application Specific Integrated Circuits), and other types of logic devices.

A circuit is said reprogrammable when its functionality can be changed. The most popular reprogrammable circuit today is the FPGA. This kind of circuit used to be essentially designed for low-volume production or prototyping. However nowadays, other advantages of these circuits are appearing, such as dynamically reconfigurable computing capability: the functionality of the circuit can be changed dynamically during operation. A FPGA is essentially composed of memory elements in which the functionality of the circuit is stored and can be easily modified. Today, FPGAs are SRAM or Flash-based. SRAM-based FPGAs are volatile and must embed a non-volatile memory in which the functionality of the circuit is permanently stored. The configuration of the circuit is loaded into the SRAM at start-up. This causes a waiting time and limits integration densities. Flash-based FPGAs are slow to write, limiting the reconfigurability capabilities. MRAM could replace these two kinds of FPGAs to achieve a fully fast and non-volatile MFPGA (Magnetic FPGA) ([1]).

Although intrinsic non-volatility of the magnetic components naturally leads to study their use in memory-based devices, it is also possible to use MTJ to add non-volatility into ASICs circuits. These circuits are not programmable and can only achieve a given logic function. This is the case of the processors for example. Today, in CMOS technology, the leakage current in transistors becomes larger and larger, so that the standby power consumption exceeds the dynamic power consumption. The introduction of non-volatility in these kinds of circuits allows switching off the power supply of unused parts of the circuit without losing information, dramatically reducing power consumption. In this objective, MTJs benefit from several advantages: their high working speed and infinite cyclability allow using them as a high-speed storage element. Furthermore, the capacity to implement them above CMOS components allows reducing the footprint of the components and multiplying as well as shortening the interconnections between logic and memory. It is then possible not only to replace the register memories by MRAM, but also to really make the circuit intrinsically non-volatile keeping a high speed in programming and/or in operation ([2]).

The design of hybrid architectures embedding magnetic and CMOS components requires developing Design Kits (DK) which allow integrating magnetic components in microelectronics design suites like CADENCE, so that complete simulations and verifications of the hybrid devices can be performed before experimental realization and testing. The two main aspects of a DK are compact modelling, to allow the electrical properties of MTJs to be simulated in standard electric simulators and physical verification tools allowing designing and checking the layout of the circuit to be manufactured ([3]).

This tutorial will address these various aspects of hybrid CMOS/MTJ electronics for applications others than MRAM.
References


Point contacts (PC) deposited on spin-valves [1] or pseudo-spin-valves [2] stacks have been introduced recently as a new category of spin torque oscillators. In these systems, the conjunction of the spin-torque and the Oersted-Ampere field created by the current favors the nucleation of a vortex in the free layer of the spin-valve. Thanks to the energy supplied by the spin torque, the vortex starts to orbit around the PC region yielding a stable sub-GHz oscillation of the PC resistance.

We will review the experimental evidences of this spin-torque induced translational motion of a magnetic vortex, and detail a protocol and a configuration to obtain vortex oscillators without ever needing an applied field. The experimental findings are consistent with a vortex executing a large amplitude orbital motion outside the point contact region. Based on this conjecture, we will then describe how to understand the free running frequency of the oscillator, that is mainly governed by the current. We will correlate the oscillation properties to quasi-static measurements of the differential resistance, and discuss the RF power effectively delivered by the oscillator.

By comparing frequency domain noise power densities with time domain voltage traces, we show that the waveform is a slightly asymmetric sine wave. The pure Lorentzian shape of the emission lines arises solely from phase noise that can be directly visualized in the time domain and related to a single relaxation time [3].

Finally, applications to compact rf oscillators [4] are usually used as advertisement for spin torque oscillator. Since most rf applications require modulation schemes, the oscillator agility -i.e. the rate at which the frequency can be effectively tuned- is thus an essential figure of merit that need to be measured and understood. Using a microwave interferometry experiment, we will show that the vortex oscillator can jump between frequencies within a few oscillation periods, and that the emission is quickly stabilized. As an illustration of this agility, we will show how to implement a frequency shift keying (FSK) modulation scheme and swap between two carrier frequencies at 380 and 450 MHz respectively every 40 ns.

References
NONLINEAR MAGNETORESISTANCE IN DUAL SPIN VALVES:
PHENOMENOLOGICAL MODEL

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We consider a dual spin valve consisting of a thin magnetic layer separated by nonmagnetic spacers from two thick magnetic layers with antiparallel magnetization orientations. When a sufficiently large current flows through such a structure, the spin accumulation in the central layer can be large enough to lead to nonlinear effects following from the energy dependence of the density of states. The latter gives rise to the dependence of the central layer’s bulk parameters, like bulk resistivity $\rho$ and spin asymmetry factor $\beta$, on the spin accumulation.

To study the influence of this effect on the magnetoresistance of dual spin valves we used a phenomenological approach based on the generalized description worked out in Ref. [1]. The dependence of bulk parameters on spin accumulation has been assumed as $\rho = \rho_0 + qg$ and $\beta = \beta_0 + \xi g$, where $g$ is average spin accumulation in the central magnetic layer; $\rho_0$ and $\beta_0$ are the equilibrium values of bulk resistivity and spin asymmetry factor, respectively, whereas $q$ and $\xi$ are some phenomenological parameters, which are characteristic of a particular material.

As shown in the figure, when magnetization of the central layer rotates in the layer plane, one finds a nonstandard variation of the magnetoresistance (calculated according to [2]). When current is flowing in a certain direction (say $I > 0$), the magnetoresistance is larger for the configuration with central magnetization parallel to that of the left layer. For current flowing in the opposite direction ($I < 0$), the magnetoresistance is larger for configuration with magnetization of central layer parallel to the right one. Such a behavior has been reported experimentally [3], and strongly differs from the conventional behavior of magnetoresistance effect, which is generally independent on the applied current (when there is no current-induced dynamics).

Magnetoresistance of Co(6)/Cu(4)/Py(2)/Cu(4)/Co(6)/IrMn(10) as a function of central magnetization direction, which changes in the layer plane. Here, $\theta$ is the angle between central and left magnetization vectors. In the calculation we assumed $\rho_0 = 16.0 \, \mu W \, cm$, $\beta_0 = 0.77$; $q = 0.1$ in the units of $1/(e I_0 l_{sf})$, and $\xi = 0.1$ in the units of $(e I_0 \rho_0 l_{sf})$, where $e$ is the electron charge, $l_{sf}$ is spin flip length in Py (5.5 nm), and $I_0 = 10^9 \, A/m^2$.

References
SPIN-TORQUE OSCILLATIONS IN ZERO MAGNETIC FIELD

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Nanoscale magnetic oscillators have proven their preeminent capacity to emit high frequency signals when a spin-polarized current is applied to the magnetization plane, transferring angular momentum to the magnetization of the system. Here, we study zero-field microwave excitations in nano-oscillators manufactured in the point-contact and nanopillar geometries. These oscillators can find applications in telecommunications, where they could be used as high-frequency signal combiners and emitters and where zero field operation is a prerequisite.

Metallic point-contacts to bottom-pinned exchange-biased spin-valves are fabricated via a 160 nm perforation in a SiO\textsubscript{2} passivation layer. When the electrical current flows across the spin-valve, it generates the appropriate Oersted field for a vortex nucleation, under a specific current-field configuration, while the spin-transfer torque drives its orbital motion around the contact region\textsuperscript{1,2} (Fig. 1). The vortex motion induces time-varying changes in the magnetization orientation underneath the contact, leading to sub-GHz voltage oscillations. These spin-torque oscillations have a current-field threshold of I = 31 mA and $H_{\perp} = 115$ mT and can be sustained for zero magnetic field, solely under a current polarity in which electrons flow from the free to the pinned layer.

Nanopillars (100x200 nm\textsuperscript{2}) have been fabricated\textsuperscript{3} from the low resistance-area product (0.9 $\Omega \cdot \mu m^2$) magnetic tunnel junctions. The critical current threshold has been determined to be $I = 1.5$ mA, considerably smaller than in point-contact systems. In zero-field, the magnetization dynamics show a broad resonance at 10.59 GHz below the threshold, where a strong non-linear enhancement in total power is seen for increasing current, jointly with a reduction in linewidth to 8 MHz\textsuperscript{4}. These oscillations are persistent for zero magnetic field (Fig. 2). Macromagnetic modeling has been performed and indicates that the frequency behavior is provided by the optical mode of the synthetic antiferromagnet system from the current convention, excluding a free layer uniform excitation.

In summary, we have demonstrated that zero-field emission in metallic point-contacts and nanopillars is achievable. It originates in distinct magnetic configurations, i.e., a vortex-based
oscillation for point-contacts and an uniform oscillation of the synthetic antiferromagnetic system in nanopillars devices.

References
The effect of thermal excitation on high tunnel-magnetoresistance magnetic tunnel junctions driven by spin transfer torque was studied by means of stochastic simulations taking into account the room thermal bath temperature and the Joule heating generated by the sample [1]. This thermal effect contribution is inputted into our micromagnetic simulations by means of a thermal random field added to effective field leading to the stochastic Langevin-Landau-Lifshitz-Gilbert-Slonczewski [2] dynamic equation.

In order to get some insight into the thermal activation mechanisms a great number of simulations were made for both transitions, whose statistics are shown in the next figures. Figure 1 shows the statistical distribution in terms of switching times for each reversal, where it’s clear that thermal energy aids in the switching event. In figure 2 we represent the average of the magnetization for the most common switching time (for both transitions). For the average, the simulations chosen were the ones with switching times no larger or minor than 25 ps, in respect to the reference central switching time. Form these results it seems that the thermal field does not add any significant new dynamics to the magnetization switching event (besides the previously seen reversal promotion), since only minor oscillations are seen prior and after the reversal.

![Fig. 1. Stochastic simulation results; (a) 1200 simulations of the AP→P transition switching time distribution; J=4.5×10^6 A/cm^2, t_{pulse}=14 ns. (b) 1200 simulations of the P→AP transition switching time distribution; J= -1.05×10^7 A/cm^2, t_{pulse}=14 ns.](image)

![Fig. 2. (a) Average of 24 events of the AP→P transition with switching time 6.725 ns ± 25 ps, with a single shot transition inset; J=4.5×10^6 A/cm^2, t_{pulse}=14 ns. (b) Average of 23 events of the P→AP transition with switching time 5.825 ns ± 25 ps, with single shot transition inset; J= -1.05×10^7 A/cm^2, t_{pulse}=14 ns.](image)
References


We study numerically the ultra-fast dynamics of magnetic bubbles in finite geometries [1]. The evolution of bubbles under an external magnetic field gradient in nanoelements is presented here. For magnetic field pulses of low strength a translational mode of the bubble domain has been excited. In order to follow the motion of the bubble and describe its dynamics, the moments of the magnetisation and of the topological density are calculated in every time step. The gyrotropic motion of the bubble is described here for the first time and the eigenfrequency of the motion is calculated (Figure 1). For higher strength field pulses a simple mechanism to create a bubble with Skyrmion number zero is illustrated. This is a state with dynamical behaviour different than the original monobubble state. A corresponding mechanism to switch back to the original bubble with Skyrmion number unity is also identified. This topological switching between the two distinct states can be achieved in an ultra-fast way in a nanostructure.

Figure 1: The orbit of the bubble under the field gradient. The solid line shows the moments of the topological density ($R_x, R_y$) and the dashed line the moments of the magnetization ($X, Y$). The circles mark the bubble position at times multiples of $3.33 \tau_0$ (15ps). The arrows indicate when the perpendicular field is switched off.

References
DOMAIN WALL BEHAVIOUR IN MAGNETIC NANOELEMENTS AND WIRES

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Domain walls in magnetic nanoelements and wires have markedly different properties from their counterparts in either thin films or bulk material. An understanding of their structure and their behaviour under external stimuli is of fundamental interest and also necessary if reliable nanomagnetic devices are to be developed. In this lecture, following a brief introduction to domains and domain walls (DWs), I shall describe how magnetic imaging can provide much of the necessary information in a direct and accessible way. Various imaging techniques exist and here the focus will be on transmission electron microscopy. In addition to offering high spatial resolution it is well suited to in-situ experimentation.

The structure of DWs in elements or wires fabricated from soft magnetic materials such as permalloy is rarely simple and three dimensional magnetic features, such as vortices, occur frequently. Moreover, the domain and DW structure in multilayer and single layer elements with the same total magnetic thickness can be quite different. This leads to fertile ground for research and offers opportunities for tailoring properties towards specific applications.

Much of the lecture will be devoted to magnetic wires and I will initially consider a straight wire of constant width. I will discuss the types of DW that can be supported and show how multiple degeneracy can arise. This leads on to a discussion of how walls can be trapped and how the same geometric variation, for example a local variation in wire width, can act as a potential barrier for some DWs and a potential well for others. Means of creating DWs will also be described with emphasis given to methods that generate a non-degenerate DW type. In all of the above a magnetic field will have been the driving force for DW creation, propagation and annihilation.

In the final part of the lecture I will discuss briefly more complex in situ experimentation whereby transport measurements and DW observation can be combined. Thereafter a simple modification to the experimental set-up allows DWs to be driven by spin-polarised current rather than by magnetic field. Some key observations from these experiments will be described.
A magnetic tunnel junctions (MTJ), which consists of an ultra-thin insulator (a tunnel barrier) sandwiched by two ferromagnetic electrode layers, exhibits tunnel magnetoresistance (TMR) effect due to spin-dependent electron tunneling. The TMR effect in MTJs is the most important technology in the field of spintronics. Since the discovery of room-temperature TMR effect in 1995 [1,2], MTJs with an amorphous Al-O tunnel barrier have been extensively studied and already used in read head of hard disk drive (HDD) and magnetoresistive random-access-memory (MRAM). These conventional MTJs show a magnetoresistance (MR) ratio (a performance index in applications) of up to about 70% at room temperature. However, MTJs with much higher magnetoresistance have been desired for next-generation MRAM and HDD. In 2001, first-principle theories predicted the MR ratios above 1,000% in epitaxial Fe(001)/MgO(001)/Fe(001) MTJs with a crystalline MgO(001) tunnel barrier as a result of coherent spin-dependent tunneling [3]. In 2004, giant MR ratios of about 200% at room temperature (RT) were experimentally achieved in textured and fully epitaxial MgO-based MTJs [4,5]. Novel CoFeB/MgO(001)/CoFeB-MTJ structure, which is highly compatible with mass-manufacturing processes was also developed [6], and giant MR ratios of up to 1,000% at RT have been obtained [7]. This large TMR effect in MgO-based MTJs is called ‘giant TMR effect’. The giant TMR effect is a key for developing next-generation spintronic devices such as read head of ultrahigh-density HDD [8], high-density spin-torque MRAM (so-called STT-MRAM or Spin-RAM) [9] and novel microwave detector [10] and oscillator [11]. In my lecture, I’m going to review the history of magnetoresistance and talk about basic physics and industrial applications of TMR effect in MTJs.

References
When combining transport with magnetic materials on the nanoscale, a range of exciting and novel phenomena emerge. It was found that the magnetization configuration influences strongly the transport due to spin-dependent scattering in ferromagnets (e.g. domain wall magnetoresistance).

Conversely the reciprocal effect of the spin polarized currents on the magnetization also exists. This “spin transfer torque” effect leads to current-induced domain wall motion, which has become the focus of intense research in the last few years due to a strong interest in the fundamental interaction between spin – polarized currents and the magnetization in ferromagnets [1].

Furthermore for applications, it has recently become possible to replace the conventional field-induced reversal by current-induced switching, which exhibits are more favourable scaling behaviour with decreasing lateral dimensions. It has become possible to engineer the domain wall spin structure in device, which then allows controlled switching by wall displacement opening up a novel avenue towards storage, logic and sensing devices.

In current-induced domain wall motion (CIDM), due to a spin torque effect, electrons transfer angular momentum and thereby push a domain wall [2]. We have comprehensively investigated this effect and observed that this interaction is strongly dependent on the temperature [3] and the wall spin structure [2]. In addition to wall motion we observe periodic domain wall transformations in line with theoretical predictions yielding further insights into the underlying interaction mechanism [4].

Dynamic measurements show that AC currents can excite non-linear domain wall oscillations at current densities below what is necessary for wall displacement. We determine the oscillatory eigenmodes and quantitatively map the non-linear potential, which can be engineered by applying external fields [5].

References
MODELLING SPIN TRANSFER INDUCED DYNAMICS; INTERPLAY BETWEEN MICROMAGNETICS AND OTHER SIMPLE MODELS

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Over the last years, significant progress has been made in modeling spin transfer torque phenomena in different systems, but a full quantitative understanding of these phenomena is still far from being complete. Micromagnetic simulations are a extremely useful tool in interpreting experimental results and gaining new insights into the physics of these processes, but sometimes they give important discrepancies with experiments, whereas oversimplified models, such as macrospin models, yield a better agreement. In this talk we will argue, by means of several examples, that both approaches are useful and complementary if one is aware of their limitations.

For instance, when modeling current induced domain wall motion in nanowires a simplified one dimensional linear model can be derived from the Landau-Lifshitz equation assuming that the wall behaves like a rigid object and that the tilt angle inside the wall is small [1]. This simple model gives a lot of insight into the physics behind domain wall motion and predicts some features observed experimentally, but it cannot take into account variations in the domain wall thickness and internal structure, which are important in some cases [2]. It will be shown, however, that the one dimensional linear model gives very good quantitative agreement with experimental data when studying the depinning process of a domain wall by means of an AC current, provided that micromagnetic simulations are used to obtain some input parameters of the model, such as domain wall width and the characterization of the pinning potential [3].

When simulating a pillar devices, on the other hand, it is noticeable that sometimes micromagnetic simulations give poorer agreement with experiment than macrospin models. As pointed out by Berkov and Miltat [4], this means that we do not understand some crucial physical properties of the system and some further research is needed. We will focus our attention on the investigation of current induced oscillations in asymmetric pillar devices in the diffusive transport limit where, under certain circumstances, an anomalous angular spin torque dependence is found [5]. Our analysis reveals that certain effects emerging from macrospin approximation, such as the occurrence of out-of-plane precession, are just model artifacts and its validity for system under study is questioned.

Finally, I will briefly discuss the challenging problem of simulating current induced oscillations in the point contact geometry. In this case, macrospin models are inaccurate when predicting frequency versus current curves, since they do not take into account for spin wave radiation outside the point contact area.

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References
COMPARISON BETWEEN A SELF-ALIGNED AND A CMP BASED NANO-PILLAR FABRICATION PROCESSES

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Nano-pillar fabrication techniques making use of a chemical-mechanical polishing (CMP) step to open a via to the pillar have proven capable of producing working devices as small as 30 nm [1]. This nanofabrication method is considerably longer and more difficult to monitor and control than the self-aligned microfabrication method [2] which is used when dealing with micron-sized pillars. This results in a reduced yield and smaller uniformity of the transport properties of magnetoresistive devices. With small modifications in key process parameters, the self-aligned microfabrication method can be extended to become compatible with dimensions down to 100nm. This modified self-aligned process was used to pattern magnetic tunnel junctions based on the stack glass // Ta(100Å) / Ru(150Å) / Ta(100Å) / MnIr(150Å) / Co\(_{80}\)Fe\(_{20}\)(15Å) / Ru(8Å) / [Co\(_{70}\)Fe\(_{30}\)]B\(_{20}\)(20Å) / Al(5.0Å) + ((5s)+(5s)+0s plasma oxidation) / [Co\(_{70}\)Fe\(_{30}\)]B\(_{20}\)(20Å) / Ta (100Å) / TiWN\(_2\)(50Å). A TMR of 27.1% is obtained in devices with 7.9 Ω\(\mu\)m\(^2\) patterned down to 100nx200nm and exhibiting H\(_c\)<1Oe after annealing at 220°C for 10 minutes (Fig. 1).

![Figure 1. Transfer curve of a 100nx200nm MTJ pillar fabricated with a modified self-aligned process.](image)

The key process parameters in the self-aligned nanofabrication process are discussed. The effect of such parameters on device transport and magnetic properties is shown.

The advantages and disadvantages of the two nanofabrication processes and their effect on spin transfer based devices are also discussed.

References
Recent results on dc current induced vortex oscillations have attracted much attention because the related microwave emissions is very coherent even if the emitted powers remain too weak, in particular in nanopillar geometry [1-3]. Here we present experimental evidences of high power, low linewidth spin-transfer induced vortex oscillations in MgO based magnetic tunnel junctions with a large TMR ratio [4,5].

Our analysis is based on a new analytical approach of spin-transfer induced vortex self-oscillations compared to the conventional Thiele formalism together with micromagnetic calculations. We will show that such MTJ devices are model systems to provide a clear picture of the mechanisms of vortex precessions induced by spin transfer. In addition, it allows us to determine the best conditions to obtain large power emissions with large quality factor.

References
Establishing techniques for efficient generation and manipulation of spin-currents is a key for further advancement of spintronic devices. In this talk I will survey the recent research progresses in terms of the spin-current induced phenomena in metallic nano-structures.

One of the above spin-current induced phenomena is the spin-transfer where the spin angular momentum carried by the spin-current is transferred to exert the spin torque on the localized magnetic moment. This provides the novel means to switch or oscillate the magnetization of nano-scale ferromagnet in Magnetic Random Access Memory. It is also important to remark that the spin torque driven magnetization reversal can be realized by using the pure spin-current generated by non-local spin injection with no net charge flow unlike the spin polarized current [1].

The spin Hall Effect (SHE) is also a novel phenomenon where the spin-orbit interaction converts the spin-current into a charge current and vice versa, known as the “direct” and “inverse” SHEs. The SHE was demonstrated first on the semiconductor systems by means of optical detection. In diffusive metals, the SHE is electrically accessible. The electrical observation of the charge accumulation due to the inverse SHE was first performed by using a nonlocal spin-injection in a lateral ferromagnetic-nonmagnetic Al metallic nano-structure [3]. This experiment was however successful only at low temperatures simply because of the long spin diffusion length, large enough with respect to the device dimensions. Separately performed inverse SHE measurement using spin pumping technique ascertained that platinum with a large spin-orbit interaction is a good candidate for further study of this sort [4]. Recent development of spin-current absorption technique enabled to detect electrically reversible SHE, the direct and inverse SHEs even at room temperature [5]. More recently giant SHE in Au [6] was demonstrated by using the same method in Ref. [3].

These results open up a new possibility to use normal metals with high spin-orbit interaction as spin-current sources operating at room temperature for the future spintronic applications.

References
CONTROL OF MAGNETIZATION DYNAMICS USING PATTERNED STRUCTURES

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High power absorption phenomena in ferromagnetic resonance provides familiar examples of threshold processes, such as subsidiary absorption. The threshold for this, and other important low order processes, is determined by rates of microwave absorption and dissipation. These rates are largely determined by intrinsic material parameters, nevertheless possibilities exist for strongly modifying process thresholds by patterning and multilayering of films.

We discuss factors impacting spin wave interaction processes in constrained geometries, and during magnetization reversal. In particular, we describe how patterning of magnetic films into wire arrays and elements can be used to modify spin wave dispersions and low order interaction thresholds. We also consider how transient dynamics, such as occur during precessional reversal, can give rise to high order processes affecting reversal rates and dynamics.

High frequency spin wave dynamics are intrinsically linked to underlying magnetic configurations. Other examples of element shape modified threshold behaviours, not directly related to spin wave dynamics, are therefore also important. Relevant cases include magnetic domain wall depinning in wires and patterned films. In these examples, we discuss briefly how low frequency magnetic dynamics and quasi-static configurations can be controlled through geometrical constraints and patterning techniques.

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Nanometre scale planar magnetic nanowires can exhibit a special magnetic property known as domain wall (DW) conduit behaviour in which DWs can be transmitted along the nanowire by the application of weak magnetic fields or electrical currents. Topographical changes such as corners, junctions, constrictions and protrusions in otherwise straight magnetic nanowires allow control of the DWs within these conduits as they create changes in the energy landscape which modify their local propagation field. This opens up the possibility of integrated circuits containing complex networks of nanowires in which information is carried, stored and processed by DWs flowing along nanowire conduits.

In this talk I describe the main features of how artificial structures such as constrictions, side arms and crossed wires modify the energy landscape of a moving DW and explain the key role that the chirality of the transverse component of the DW plays in understanding how DWs interact with artificial structures. I show how DWs interacting with each other can be measured experimentally using a 'near-pass' pair of conduits, how the DW chirality can be probed through a 'chirality filter' formed from a crossing nanowires [1] and how a high efficiency DW-gate (the DW equivalent of a transistor) can be formed from a T-stub nanowire [2]. Finally, I demonstrate a working non-volatile 32-bit memory block with four electrically integrated inputs based on nanowire shift registers.

References
In the recent years a large increase of activity in the field of magnetic logic took place. The advent of technologies capable of producing patterned plane magnetic structures largely stimulated this activity. The possibility to form logic gate arrays is a new field of application, offering a common device platform for storing and computing data with the ability to reconfigure hardware using software.

In the talk the magnetic logic functionality exploiting magnetostatic field dynamics is demonstrated. It is experimentally showed that microwave excited magnetostatic spin waves (SW) in a chain of spins can be used to perform logic operations.

The proposed concept of a spin-wave (SW) logic gate is based on a Mach-Zehnder interferometer approach. The gate mainly consists of a splitter that divides the power of the applied SW pulses into two channels (called the interferometer arms), two controllable phase shifters and switchers integrated into the arms, as well as a combiner where the signals modified in the arms interfere. Logical input signals are applied to the gates which vary either the phase or the amplitude of the spin waves in the interferometer arms. The logical output corresponds to the amplitude of the interference signal. By controlling the accumulated phase in one of the arms and keeping the phase at the output of the second arm constant one can implement a NOT gate. The possibility to shift the phases in both arms by $\pi$ allows the implementation of the XNOR operation. With the additional ability to quickly manipulate the wave amplitudes using SW switches it is possible to create a NAND gate. Implementing a universal NAND function is generally considered being of major importance, since combining several universal gates of the same type allows one to construct other gate types.

The interferometer arms are realized as longitudinally magnetized SW waveguides made from a single-crystal yttrium-iron-garnet (YIG) film. Traveling spin waves are excited and received by microstripe antennas. In order to develop the on-chip SW logic gates a SW splitter and a combiner were fabricated by structuring the YIG film. The corresponding film structures have the shape of a fork and consist of two interferometer stripe-shaped arms (prongs of the fork) and a combiner/splitter part (handle). Interference of spin-wave pulses in the combiner was studied using time and space resolve Brillouin light scattering spectroscopy. The output signal can easily be read out by an optical BLS probe in the center of the output part of the waveguide or by using a microwave transducer to sum up the amplitude over the complete pulse.

At the end of the talk the abilities to use the caustic sub-wavelength spin-wave beams formed due to anisotropy of wave propagation in a two-dimensional magnetic media as well as dynamically controlled magnonic crystals for creation of spin-wave logic gates are discussed.

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POSTERS
COMPARISON BETWEEN LIFTOFF AND POLISHING METHODS FOR NANOPILLAR DEVICE FABRICATION

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For most applications in spintronics, submicron devices are needed, usually nanofabricated under a perpendicular architecture, where the nano-feature is usually defined by electron beam (e-beam) lithography. Even more important than optimizing the e-beam exposure conditions by them self, is the nanofabrication technique used for the complete integration of the nano-feature in a top/bottom electrical contact device.

At INESC-MN a RAITH 150 tool and a negative e-beam resist (AR-7520.18) are used to define sub-micron features. To integrate the nano-sized pillar in MTJs devices two different approaches are being used: Chemical Mechanical Polishing (CMP) and Lift-Off (LO) process.

In the CMP approach, a thin resist (~80 nm) is used allowing the definition of features down to 30 nm [1]. This thickness was chosen because it allows the definition of small features (close to the limit of the machine). Since the path of the electrons in the resist is short, low energetic beams are required (10 kV, 10 µm of aperture leading to a beam current of around ~18 pA). Dimensions between 30 nm-200 nm are defined with doses between 120-40 µC/cm². After the nano pillar definition the e-beam resist is removed and a thick layer (~2000 Å) of SiO₂ is deposited and polished using slurry that chemically enhances the removal of the SiO₂. This step is used to remove the oxide from the top of the pillar leaving the oxide elsewhere in order to isolate the bottom contact from the top. Drawback of this process is the non-homogeneous polishing rate (strong dependence on feature area and density across the sample), which is the cause of reduced yield in samples processed using the CMP method. The advantage of the CMP method is the possibility of defining device features as small as 30nm [1].

In the lift-off process a pattern is defined by e-beam and without removing the resist a layer of oxide is deposited all over the sample (~500Å of Al₂O₃) covering resist and areas in which the resist has been cleared. During the lifting-off, the e-beam resist under the film is removed with solvent, taking the oxide with it, and leaving only the oxide that was deposited directly on the sample. CMP is affected by the complexity of finding an end point for the polishing while the LO process is limited by the fact that this technique is more effective for bigger feature sizes, thus limiting the minimum device dimensions to ~100 nm.

The key point for a successful LO process is related with the ratio between the resist and the oxide thicknesses. The thickness of the resist should be high and the oxide thickness low enough to be possible to perform the lift-off. However, the oxide layer should have a thickness capable of doing an effective isolation between the bottom and top electrodes. For micron sized features the LO is done using a 1.5 µm-thick of positive photoresist in e-beam lithography. In order to achieve smaller dimensions, much thinner resists (80nm-200nm) are used. For the LO process, e-beam exposure conditions were optimized for resist thicknesses of 200 and 500 nm. The strategy was to use a more energetic beam in order to enhance the incursion of the electrons in the thicker resist, 20kV of electrons acceleration voltage and 10 µm of aperture which corresponds to a current of ~25 pA. For a 200nm e-beam resist was possible to define features between to 60 nm – 1 µm with doses 165-60 µC/cm². In the case of the 500nm-thick resist the same dimensions were obtained with doses of 228-80 µC/cm². Drawback of this process is the control of the oxide liftoff, as it requires individual device
inspection in the SEM microscope.

In this work we show results on devices nanofabricated using either methods, comparing the yield (over 500 devices per sample), and the process time flow. The choice between either methods depends essentially on the minimum feature dimensions required for the nanopillars and on the reliability of the polishing method.

References
This work describes the characterization of MgO based magnetic tunnel junctions (MTJs) prepared under several methods, aiming the optimization of barrier robustness for spin transfer measurements. The first set of devices was deposited by Ion Beam deposition [1] at INESC-MN, with the structure Si/Al2O3(500Å)/Ta(50Å)/Ru(200Å)/Ta(50Å)/Mn75Ir25(150Å)/Co90Fe10(30Å)/Ru(8Å)/Co56Fe24B20(40Å)/MgO(t)/Co56Fe24B20(30Å)/Ru(30Å)/Ta(50Å)/TiWN2(500Å). The samples were patterned into nanopillars at INESC MN by ion milling and using a chemical-mechanical-process [2], down to 48×181 nm² junction areas. The devices exhibit resistance area (RA) product of a few W.µm² and tunneling magnetoresistance (TMR) ratio of up to 35%. The average switching current density of 5.45×10⁶ A/cm² is obtained from the spin transfer switching experiment.

In order to explore the optimal preparation conditions for MgO barrier to improve the breakdown voltage of devices, a second series of samples (deposited at Crocus Technologies) were analyzed, where different preparation methods were used for the oxidation of an Mg metallic layer. Electrical characterization shows that MTJs with the tunnel barrier prepared by the plasma oxidation of Mg film have a higher breakdown voltage than those fabricated by natural oxidation. Moreover, the most robust barrier is obtained by the plasma oxidation of Mg film by means of RF power of 100W for 20 seconds.

References
We present an experimental and theoretical study [1] of the mode frequencies of thermally excited spin waves in rectangular shaped nanopillars of lateral size 60 x 100 nm², patterned from MTJ of composition CoFeB (3 nm, free layer)/ Mg (1.3) [nat ox]/ CoFeB (2)/ Ru (0.8)/ CoFe (2)/ PtMn (20), where the three layers following the MgO tunnel barrier compose the synthetic antiferromagnet (SAF). The spin wave spectra (mode frequencies versus easy and hard axis applied field) of individual devices were obtained using spectrally resolved electrical noise power measurements.

In all spectra, several independent quantized spin wave modes stemming from eigenexcitations of the free layer and the SAF layers of the MTJ have been observed. By modeling the nanopillar as a system of three coupled, spatially confined magnetic layers with uniform equilibrium magnetization and diagonalizing its dynamical matrix, we have calculated the frequencies of the different spin wave modes, obtaining quantitative agreement with the experiment at high and medium fields. Taking into account the mode character sensitivity of our measurement technique, we could identify the various modes and extract the material parameters of the pillar. The magnetization and exchange stiffness constant of the CoFeB free layer are found to be significantly reduced compared to the values for the corresponding unpatterned thin films, while the interlayer exchange coupling and the exchange bias of the SAF are essentially consistent with their thin film counterparts. The interlayer dipolar coupling between the different layers could be well described in terms of an effective mutual dipolar coupling in diagonal tensor approximation. In particular the dipolar coupling of the free layer to the SAF layers has been found to be crucial for reproducing the experimental spectra. Finally, we could infer from the frequencies and relative intensities of the modes that the pinning of the magnetization at the lateral boundaries must be weak and slightly asymmetric. At low fields, the lowest mode is in many devices not the quasi-uniform fundamental mode, but a mode localized near the layer edges. The character of both mode types is corroborated by micromagnetic simulations.

Acknowledgments

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References

CURRENT-INDUCED MAGNETIZATION SWITCHING IN MAGNETIC TUNNEL JUNCTIONS WITH CoFeB/Ru/CoFeB SYNTHETIC FREE LAYER

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The important issue for MRAM applications is the minimization of critical current density in magnetic tunnel junctions (MTJs) necessary for current-induced magnetization switching (CIMS). One of the possible solutions proposed by J. Hayakawa et al. [1] is the substitution of the standard CoFeB free layer with the synthetic antiferromagnet (SAF). Patterned MTJs prepared by ion-beam assisted deposition (nanopillars, sizes down to 60 nm × 80 nm) with 2 nm CoFeB free layer and CoFeB/Ru (t$_{	ext{Ru}}$=0.71 nm and 0.92 nm)/CoFeB SAF as a free layer were studied. Thickness of the free layer Ru spacer varied in order to provide optimal antiferromagnetic coupling between two ferromagnetic layers, thus improving thermal stability of the MTJ and reducing switching current density. We have measured critical current density (Jc) of CIMS with various pulse lengths. MTJs with SAF demonstrated lower values of Jc and higher thermal stability in comparison to MTJs with standard free layer.

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References
TEM CHARACTERISATION OF CoFeB ULTRATHIN FILMS FOR MTJ SENSOR APPLICATIONS

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Magnetic tunnel junctions (MTJs) have been extensively studied in view of their technological applications as magnetic random access memories (MRAM) or high sensitivity field sensors. The achievement of high TMR values and a low level of noise are crucial in the construction of reliable magnetic devices. Although large TMR has been realised by using CoFeB [1] as the pinned and/or free layer material with MgO as the barrier [2], the fulfillment of low noise level devices is still a challenge.

Wisniowski et al. [3] have explored the possibility of reducing the noise in MTJ sensors by varying the thickness of the free layer. They found that below a critical thickness (15.5 Å) the MTJ transfer curves become hysteresis-free, but this was achieved at the expense of a fall in TMR.

A deeper understanding of this result can be achieved by using conventional TEM and Lorentz Microscopy to characterise respectively the physical microstructure and the domain structure of the CoFeB free layer when its thickness varies between 30 Å and 14 Å, which is the same thickness range used in [3].

As regards the physical microstructure, the TEM images show that the CoFeB layer has grown as a polycrystalline thin film without evidence of discontinuities in all samples observed to date. The grain size was the only parameter which underwent a slight change, from 10 nm in the sample with 30 Å CoFeB to 5 nm in the sample with 14 Å CoFeB. The magnetization reversal mechanisms observed during Lorentz TEM experiments are found to be dependent on the applied field orientation with domain processes and magnetization rotation being observable in all samples observed to date. However, where they exist, the domain structures supported are different although all samples exhibit uniaxial anisotropy. The maximum density of domains increases as the magnetic layer thickness decreases and an increase in the ripple contrast has been observed when reducing the CoFeB thickness from 30 Å to 14 Å. The persistence of domains, even with high applied magnetic fields, has been also observed. An asymmetric magnetisation reversal was found to occur in the sample with 14 Å CoFeB layer, thus requiring further investigations in order to explain quantitatively this interesting behaviour. Recourse was made to a modified Stoner–Wohlfarth model [4] and calculations have been carried out by using a Matlab code. Progress on all these experiments and calculations will be here presented.

References
SPIN TRANSFER INDUCED VORTEX OSCILLATIONS IN SINGLE AND MULTI-NANOCONTACTS

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It is well known that in nanoscale magnetic devices, the spin transfer torque can induce a precession of the magnetization by the pure electric way. The microwave oscillation of the voltage across such devices is particularly of interest for the next generation of telecommunication devices. Sustained precession of spatially uniform magnetization has been intensively studied these last years but the emitted power and the quality factor of the STNOs (Spin Transfer Nano Oscillators) remain too low to consider a rapid transfer to applications [1]. More recently, non uniform magnetic configurations such as magnetic vortices have been considered and some spin transfer induced vortex dynamics has been detected in spin valves nanopillars [2] and nanocontacts [3].

In this work, we study the emission response of single- and multi-point contact devices. The magnetic structure is a sputtered deposited multilayer consisted of a 5-nm-Ta / 40-nm-Cu / 4-nm-Py bottom electrode, a 6-nm-Au spacer and a 15-nm-Co / 100-nm-Au top electrode. The devices were fabricated by a real-time controlled AFM nano-indentation technique. Contact of 20 nm could reliably be achieved.

In single point contact devices, we observe a single sub-GHz RF peak along with harmonics of several orders recorded with a out-of-plane magnetic field. The emitted signal is characterized by a large power (up to 1 nW/mA²/GHz) and narrow linewidth (< 10 MHz). The frequency increases with the bias current. A hysteretic behavior for the switch-on/switch-off currents is observed. In parallel, we have performed some micromagnetic simulations showing that the output power is indeed ascribable to the gyrotropic precession of the vortex core stabilized in the thick Co layer and orbiting outside the contact area [3].

The multi-point contact device consists of 2x2 matrix of nanocontacts with an intercontact spacing d = 500 [4]. Without applied field, at low bias current, the power spectrum consisted of four uncorrelated peaks associated with the orbital precession of the four vortices around the four contacts. At larger bias currents, the four peaks merge into a single peak. The merging is accompanied by a sudden increase of the power amplitude and a significant narrowing of the linewidth (narrowest measured linewidth Δf = 0.9 MHz). This behavior is indicative of coherent synchronization of the four vortex based oscillators. In the presence of an in-plane field during nucleation, we observed correlated multiple peaks. The study of these multimodes gives an insight into the stability of such a system.

References
Micromagnetism can be regarded as the formalism capable of linking experimental results with theories about magnetic interactions. Up to now, micromagnetism has proved to be a very useful tool to gain the qualitative understanding of the experiments based solely on magnetic interactions. Lately, this formalism has been expanded in order to take into account the effects observed when spin-polarized currents interact with magnetic configurations at the nanoscale [1] with good qualitative agreement but clear quantitative disagreement. In this work, we report the advances made on the numerical calculation of spin accumulation due to non-uniform magnetic configurations using the model proposed by Zhang and Li [2]. By integrating the calculated spin accumulation into our home-made micromagnetic code, we are able to study the interaction between domain walls in nanowires, and spin polarized currents flowing in plane (CIP). Three types of domain wall configurations have been studied Symmetric Transverse (STW), Asymmetric Transverse (ATW) and Vortex (VW). We report the results of the interactions between these magnetic configurations and in-plane spin polarized currents.

References
COMPUTATIONAL STUDY OF MAGNETIZATION DYNAMICS IN NONSTANDARD SPIN VALVES

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The current-induced spin-transfer torque in a spin valve structure where magnetic layers are made of different materials can exhibit a nonstandard, i.e. 'wavy'-like angular behavior [1] provided that the torque is calculated in the diffusive transport limit. This kind of behavior has been found theoretically in the Co(8 nm)/Cu(10 nm)/Py(8 nm) spin valve, and was later also confirmed experimentally [2], [3]. The unique property of the 'wavy' torque allows for the microwave generation in absence of the external field, which is of particular interest for the application of such oscillator.

Both, in-plane and out-of-plane precession modes have been indentified in our computational study. However, one should consider that the first one does not provide enough output power to be considered useful for further investigation. Therefore, we have concentrated on the explanation of the triggering mechanisms for the out-of-plane precession modes including both the external field and internal factors like the demagnetizing and the exchange field. The numeric study has been carried out starting with macrospin approximation and later a comparison with the full micromagnetic model has been done. Even though the macrospin model failed to describe the real behavior of such a pillar structure, it has proven to be a useful tool verifying the assumptions of the micromagnetic model. In particular the underestimation of the exchange field showed to have played crucial role in the out-of-plane precession mode generation.

Finally our results, providing first micromagnetic data on the 'wavy' torque driven dynamics, have been compared to the available experimental data [3]. The phenomena reported in [3] that were beyond macrospin scope have been successfully predicted in the full micromagnetic frame.

References
Here we report on our work on imaging the spin wave distribution at and near a nano-contact on an extended spin-valve structure using Brillouin light scattering microscopy (BLS) and on identifying relevant magnon scattering processes.

We have investigated the magnetization dynamics in the free layer of one extended spin-valve stack (IrMn(6nm) / Co_{90}Fe_{10}(5nm) / Cu(3.5nm) / Ni_{81}Fe_{19}(7nm) – free layer) with an 80 nm point contact in diameter and an asymmetric top electrode. In the presence of an external magnetic field applied in plane of the sample, the structure was subjected to a combined microwave and direct current. The magnetic resonance frequencies are determined for different externally magnetic fields. The spin-waves emission from the contact is studied for several applied microwave frequencies and as a function of the applied power from the microwave source. The results show that strong nonlinear spin waves are excited, namely the generation of eigenmodes with higher frequency (2f, 3f) but also modes with a non integer-factor (0.5f, 1.5f) with respect to the excitation microwave frequency f. The nonlinear modes are associated with three-magnon-scattering processes. Working at fixed applied microwave frequency, the intensity of the resonance mode present a linearly increase with the applied microwave power. The appearance of spin waves with half the excitation frequency shows a threshold behavior as a function of the applied microwave power. Under the influence of a direct current, a strong nonlinear dependence of the threshold power with increasing the current is measured. The observed influence is not compatible with spin transfer torque effect which should give a linear decrease of the internal damping due to three magnon splitting processes with increasing the direct current. The behavior of the power threshold can be related to the inhomogeneities of the internal field in the free layer within the point contact area, due to the Oersted field created by the direct current flowing through the asymmetric top electrode.

Support by the EC-MRTN SPINSWITCH (MRTN-CT-2006-035327) and by the DFG within the SPP 1133 is greatly acknowledged.
SYMMETRIC MAGNETIC TUNNEL JUNCTIONS WITH ENHANCED AND STABLE TMR RESPONSE

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A standard magnetic tunnel junction (MTJ) consists of a soft ferromagnetic (FM) layer (free layer) separated by a dielectric layer (DL) from a second FM layer (pinned layer) which is in contact with an antiferromagnetic (AF) layer [1]. MTJs made of alternating layers such as FM metals (Fe, Co, Ni, or their alloys) and dielectric layers (Al₂O₃, MgO), have attracted much interest since they exhibit large tunnel magnetoresistance (TMR) response at room temperature [1].

The tunneling of electrons through the DL is spin-dependent and thus is modulated by the relative orientation of FM layers (free and pinned FM layers). Recently, amorphous ferromagnetic materials such as FeCoB are used as electrodes for magnetic tunnel junctions due to the good soft magnetic properties (i.e. almost zero magnetostriction) [2]. The (Fe₀.₅₈Co₀.₂₅B₀.₁₇)₁₀₀₋ₓMₓ films present perpendicular anisotropy and thickness dependence of magnetic properties. These inconveniences can be avoided by the addition of Ni which improves the soft magnetic properties of the FeCoB film as well [3]. Because the tunneling current density is usually small, MTJ devices tend to have high electrical resistance. Recent researches are concentrating on the increase of the magnetoresistance and the decrease of the tunneling resistance by using MTJs with double exchange biased fields [4]. Symmetric spin valves are important both for the fundamental understanding of spin-dependent electron transport and their utilization for device applications.

The aim of the work was to produce symmetric MTJ structures with increased TMR response and decreased tunneling resistance. The influence of the Ni and Ni-Si additions on the TMR response, saturating magnetic field and thermal stability of symmetric FeMn/FM/Al₂O₃/FM/FeMn MTJs, with FM = (Fe₀.₅₈Co₀.₂₅B₀.₁₇)₁₀₀₋ₓMₓ (M = Ni, Ni-Si) is presented. The research work has one major motivation, namely to develop a robust MTJ structure that produces a large and thermally stable TMR effect.

Symmetric Ta (5)/Ni₈₀Fe₂₀ (5) /Fe₄₅Mn₅₅ (8)/ FeCoBΝiΜ(3.5)/Al₂O₃(1)/FeCoBΝiΜ (5)/ Fe₄₅Mn₅₅(8)/Ta(5) MTJs (M = Ni, Ni-Si) with two ferromagnetic layers exchange biased in opposite directions due to simultaneous presence in the MTJ’ centre of a Al₂O₃ (1 nm) layer under a 20 G magnetic field applied during deposition have been prepared. The TMR ratio of the symmetric Ta(5)/Ni₈₀Fe₂₀(5)/Fe₄₅Mn₅₅(8)/FeCoBΝiSi(3.5)/Al₂O₃(1)/FeCoBΝiSi(5)/ Fe₄₅Mn₅₅ (8)/Ta(5) MTJ structure has varied with about 6% for a magnetic field of up to 20 G, leading to a sensitivity of about 0.3%/G. This structure exhibits a field window of about 10 G, low values for the tunneling resistance of about 120 Ω, and a temperature coefficient of resistance (TCR) of about + 60 ppm/°C.

References
Multiferroic BiFeO3 is an attractive and intriguing material because it exhibits both ferroelectric and antiferromagnetic orders at room temperature. Such multiferroics are very promising for such application in spintronics as multiple-state memory devices with dual magnetic and electric control. For the technical application of BiFeO3 it is important to know its domain structure, but antiferromagnetic order makes the description of the domain structure in this material more difficult.

Based on the assumptions about magnetoelastic nature of antiferromagnetic domains [1] it is shown that in certain conditions the electric and the antiferromagnetic domains in the BiFeO3 crystal are strongly interrelated. This fact makes it possible to control domain structure of the sample with both electric and magnetic fields. Particularly, the switching of the electric polarization by a magnetic field is possible. In the present paper we explored such states with interrelated magnetic and electric domains and theoretical ways of reaching those states.

References
Recently, the magnetic response of a pinned storage layer for thermally assisted MRAM was characterized by single-shot real-time measurements by applying a heating pulse current density of $4.7 \times 10^6$A/cm² under a 50Oe direction setting field. The switching probability versus pulse duration exhibited characteristic periodic steps due to a combined effect of the applied field and spin transfer produced by the heating current pulses. This work investigates the expected similar switching probability periodicity in a non-exchange biased ferromagnetic layer, and the differences between pinned and non-pinned layer reversal dynamics. The switching probability was measured with a new experimental method not described here. In the studied range, the switching probability is between 65 and 95% for pulse widths between 4.8 and 5.5ns. The probability features show a period of about 0.25 ns (cf. Fig. 1), which is the same order of magnitude as the 0.35ns period reported for the CoFe 2/ NiFe 3/ IrMn 6.5nm pinned storage layer in Reference 1.

![Figure 1: Switching probability as a function of applied pulse width. Dots are experimental data. Continuous line is the average of the experimental dots on the 10 closest neighbours. It shows a step-like behaviour.](image-url)

**References**

MAGNETIC VORTEX CORE DYNAMICS IN PERMALLOY DISCS

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The recent discovery that a spin-polarized current can induce magnetic vortex dynamics opened a new way to manipulate magnetization. Herein, we report on the resonant excitation of a magnetic vortex core in a 1 um permalloy disc (Fig. 1) due to the injection of high frequency current. The resonance is detected by the DC voltage generated by the rectification of the microwave signal due to magnetoresistance oscillations at resonance (homodyne detection) [1]. Strong shifts of the frequency with the in-plane magnetic field are observed, which indicate the presence of local pinning (Fig. 2). By a systematic study of the resonance frequency over a wide range of magnetic field angle and amplitude, we were able, in combination with micromagnetic simulation, to deduce the dependence of the resonance frequency on the vortex core position. According to the theoretical estimation of the trajectory of the magnetic vortex core gyration [2], we obtain the diameter of the oscillations and the phase shift between the microwave current and the magnetoresistance oscillations as a function of the position of the vortex core. Moreover, we observed the strong depinning process at the pinning sites due to increasing microwave power.

![Fig. 1. SEM image of Permalloy disc.](image1)

![Fig. 2. The measured and simulated resonance frequencies as a function of field and angle.](image2)

*This work was supported by the EU-RTNs SPINSWITCH (MRTN-CT-2006-035327).

**References**
RF OSCILLATORS USING A MAGNETIC TUNNEL JUNCTION AND A PERPENDICULAR ANISOTROPY POLARIZER


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The growing number of wireless microwave applications (mobile phones, GPS etc) requires a device that is able to cover a large frequency range upon keeping the system size low. Here the extremely small size of spintronics based RF oscillators (100nm) provides a promising solution for these futures devices. In such spintronics based oscillators it is the spin transfer torque effect that induces periodic oscillations of the free layer by a spin polarized current.

Previous studies in our laboratory were performed for RF oscillators based on a spin valve with a perpendicular polarizer and a planar free layer [1]. The perpendicular anisotropy polarizer leads to out-of-plane precessions of the magnetization in the in-plane anisotropy free layer with significant high amplitude in zero effective bias fields. However, in order to significantly enhance the output power, it is essential to use a magnetic tunnel junction (MTJ) combined with a perpendicular polarizer. The goal of this study is to develop a low resistivity MgO barrier to realise a double barrier junction associating a perpendicular anisotropy spin polariser to a MTJ structure.

The role of the MTJ insulating barrier is critical to obtain a high TMR signal. A crystalline MgO barrier is usually used because of its high TMR signal. The use of such a barrier requires a resistance area (RA) product of only few $\Omega \mu \text{m}^2$. In order to decrease the RA, one needs to reduce the MgO thickness which can generate an inhomogeneous barrier. Recently, several results demonstrated that the insertion of a thin Mg layer deposited on the bottom ferromagnetic electrode prior to the MgO barrier deposition enhances the TMR signal at low RA values [3-4]. We show that an Mg insertion below and above the MgO barrier at low RA regions allows us to reduce the MgO thickness. Probably the Mg insertion avoids pinhole formations.

Another aspect of this work is the development of a perpendicular anisotropy polarizer. We have compared two different systems: Pt30/Co1/Cu3/Co1 and Pt30/ [Co0.5/Pt0.4]5 /Co1/Cu0.3/Co1 (thickness in nm). The measurements were made by Extraordinary Hall Effect (EHE) using a perpendicular-to-plane field. The insertion of a Co/Pt multilayer enhances the coercivity due to a greater interfacial anisotropy and a ferromagnetic exchange bias between the multilayer and the Co1/Cu0.3/Co1 layer. Also the spacer between the perpendicular polarizer and the MTJ was studied by EHE measurements on in-plane field. The oxide alumina spacer presents higher perpendicular anisotropy in comparison to a metallic Cu barrier. Thus, the interface plays a fundamental role to induce perpendicular anisotropy.

Our goal is the fabrication of a RF oscillator with a perpendicular polarizer and a low RA magnetic tunnel junction. At this step, we were able to fabricate a magnetic tunnel junction with an MgO barrier of an RA product of approximately 5 $\Omega \mu \text{m}5$ and a TMR ratio of 50% due to Mg insertions. Perpendicular polarizer based on multilayer of Co/Pt and Co/Cu/Co with a spacer in alumina presents the magnetic properties expected for our final structure.

References

OFF-AXIS Al DEPOSITION FOR LOW RESISTIVITY TUNNEL BARRIERS

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Spin Transfer Torque Magnetic Tunnel Junctions (STT-MTJ) are usually considered as the most promising candidate to achieve scalable low consumption MRAM cells [1, 2]. The breakdown voltage of the tunnel barrier sets the maximum current density that the tunnel junction can sustain. Therefore resistance area products below $10 \Omega \mu m^2$ are required to achieve typical switching current densities of $10^6$-10$^7$ A/cm². This work reports on AlOx tunnel barriers obtained by natural oxidation of an ultrathin Al. It was found that the TMR ratio significantly depends on the offset between the wafer and the target axes during the Al layer deposition. When the Al layer is sputtered on axis, the TMR ratio is only 10.7%, whereas the off-axis sample showed a TMR ratio of 28.7% for the same RA product of $14 \Omega \mu m^2$. We assume that the off-axis deposition allows reducing the bombardment of the substrate by Ar ions or reflected neutral Ar atoms, resulting in a higher barrier quality, because of lower damage and/or incorporation of Ar in the Al barrier and bottom CoFeB layer as well as sharper interfaces.

Fig. 1: Dependence of the TMR ratio and RA product on the Al layer thickness for both configurations. The barrier quality is improved when the Al layer is deposited off-axis, leading to an increase of TMR from 10.7% to 28.7%. The RA product is the same: $14 \Omega \mu m^2$.

References
FABRICATION AND MICROSTRUCTURING OF DIFFERENT TEMPLATES FOR MAGNETIC MULTILAYERED NANOWIRES DEPOSITION

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The preparation of different templates by anodisation of different substrates in various acidic electrolytes has attracted considerable attention in recent years because a variety of nanostructures (metal and semiconductor as well as multilayered) have been produced by electrochemical deposition within their nanopores of the anodic aluminium oxide (AAO), titania template and silicon templates.

In this work, we investigated the influence of anodizing conditions (like acid concentration and temperature) on the characteristics of alumina, titania and silicon membrane. We obtained titania membranes with pore diameter between 20 nm and 150 nm by changing the anodisation conditions such as the applied voltage. The thickness of the obtained templates is about 2µm. The nanopores of the silicon membranes which are obtained in this work can’t be used to obtain nanowires because they are not parallels. The AAO membrane was prepared following the two-step anodisation procedure at 40V, in an oxalic acid solution of 0.3M and 0.4M at 15°C and 19°C, respectively. The obtained membranes were characterized by scanning electron microscopy (SEM) using a JEOL microscope. We observed that the growth rate of oxide layer is changing with acid concentration. A typical AAO image indicates that the nanopores are hexagonally arranged.

The nanopores of the AAO template were filled with NiFe/Cu magnetic multilayers nanowires by electrodeposition and we observed that the diameter of the nanowires is equal to the one of the nanopores. The electrodeposited alumina samples were submitted to a mechanically polishing process. Figure 1 shows the top view SEM micrographs of a highly ordered alumina pore structure filled with NiFe/Cu magnetic multilayers nanowires.

![Figure 1: Top view SEM micrographs of a highly ordered alumina pore structure filled with NiFe/Cu magnetic multilayers nanowires.](image-url)
THE NATURE OF TWO-LEVEL SYSTEMS IN AMORPHOUS MATERIALS AND DISORDERED CRYSTALS

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The dynamical defects in amorphous systems or disordered crystals are described as ensembles of two-level systems (TLS). To account for the anisotropy in the sound absorption observed in disordered crystals and to be able to describe in general the interaction of TLS with phonons or strain fields in mesoscopic systems, we introduced a new model of TLS [1,2]. In the new model we associate a direction in space to each TLS and the coupling of a TLS with an elastic disturbance is done through a 4-dimensional array of coupling constants, the structure of which being determined by the symmetries of the crystal [1-5].

We apply the model to explain the asymmetry of the sound absorption in disordered crystals of different symmetries and the orientation dependent TLS-TLS interaction [6].

References
GREEN'S FUNCTIONS ON FINITE LATTICES
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The method of lattice Green’s functions (LGF) is widely used in condensed matter when the size of the lattice is virtually infinite. Solution of the Schrödinger equation is then obtained in terms of Fourier integrals over momentum. For most lattice types explicit expressions of the LGF are known for quite some time. However, this is not the case when the finite size of the lattice and boundary conditions are physically relevant. The reason is that both direct and reciprocal spaces are then described in terms of discrete Fourier transform, which is usually employed as a device for numerical solution, e.g. via FFT. In [1] and references therein it has been shown that explicit expressions can be obtained by applying a lattice translation operator to the “usual” (infinite lattice) LGF. Non-periodic boundary conditions can be treated by doubling the lattice size. For systems in one space dimension (finite quantum chains) this approach produces results equivalent to those found by Bethe ansatz. Moreover, it is workable in higher dimensions too, offering at the same time a transparent physical picture of the quantum excitations. For instance, the problem of interacting magnons (ferromagnetic periodic Heisenberg model) reveals the existence of other excitation modes [2] in addition to the common ones (e.g. Ch. 5.5 in [3]). Their distinctive feature is that they recover the initial phase not on a single, but on a double, triple, etc. lattice length. For bound magnon states (quantum counterpart of solitons) the energy of such modes is strongly dependent on the size of the system (logarithmic), unlike the energy of the simple periodic excitations. The expression of the LGF for a two dimensional finite system does not correspond to a known special function and is given in a form of single integral, well suited for asymptotic expansion. In the particular case of a square lattice we find 5 symmetry types of bound two magnon excitations instead of 2 (“s” and “d”) known from earlier works, thus proving the efficiency of the approach.

References
We hereby report the main results of our research related to the study of size effects in switchable materials. The model we chose is a simple Ising system comprised of molecules having two states, +1 and -1, respectively. The calculations were performed by means of a Metropolis Monte Carlo algorithm. We started by developing the hypothesis of the mean field approximation [1], and then we added short range interactions between the nearest neighbors of the particles. These features correctly describe spin crossover compounds, and were used to model relaxations from the high spin (HS) metastable states to the low spin state (LS), but they can also address other issues, such as the hysteretic behavior of magnetic systems.

The study revealed a strong correlation between the number of particles in the system and the values of the switching time. It seems that the short range interactions contribute to cluster formation which considerably varies in the case of small lattices, causing large fluctuations of the amount of time required in accomplishing a transition from one state to another. As the number of molecules increases, this effect diminishes due to its statistical nature. Computations provided evidence of a Gaussian distribution of the switching time [2]. The variance of the distribution is proportional to the square root of the number of molecules, while the mean value remains the same, irrespective of the lattice size. Each distribution was obtained from a number of 50000 simulations under the same conditions and they were computed for system sizes up to 400000 particles.

References
MAGNETORESISTANCE AND CURRENT-INDUCED MAGNETIZATION REVERSAL OF SINGLE NiFe AND MULTILAYERED NiFe/Cu NANOWIRES

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After the observation of the GMR effect and its use in high-density magnetic recording media and novel magnetic sensors, the interest for nanostructured magnetic materials increased significantly.

The nanowires, because of their dimensions and unique characteristics, exhibit unusual physical properties, which make them exciting from both fundamental and technological point of view. Magnetic nanowires, in particular, are very interesting from the point of view of the spin-dependent electric transport phenomena. There are many different ways to produce nanowires, but one of the cheapest ways is the electrochemical deposition, which avoids the difficulties inherent to the nanolithography processes and allows producing important amounts of nanowires in relatively short periods of time.

In this study we focused on the magnetoresistance of single NiFe and multilayered NiFe/Cu nanowires in the current-perpendicular-to-plane (CPP) geometry. The measurements done on a number of nanowires (tens to hundreds) are compared with those obtained for individual nanowires. As parameters we used the diameter and length of the nanowires, the number of consecutive sequences and the thickness of each sequence for multilayered structures, but also the external magnetic field. For both multiple and individual nanowires in contact, the variation of the resistance with the magnetic field has a Gaussian shape behavior. For multiple wires in contact the maximum MR is $\Delta R \sim 0.6\%$, while for individual nanowires the maximum MR reaches $\Delta R \sim 1.5\%$.

We studied also the influence of the spin polarized current on the magnetization of the ferromagnetic layers. According to the pioneering work of Berger [1] and Slonczewski [2], large spin polarized current densities, passing through a ferromagnetic layer are able to change the orientation of the magnetization at the ferromagnetic layers. This phenomenon can be observed when current is flowing through two magnetic elements separated by a thin non-magnetic spacer layer. The current becomes spin polarized by transmission through or on reflection from the first magnetic layer and mostly maintains this polarization as it passes through the non-magnetic spacer layer and enters and interacts with the second ferromagnetic layer. The interaction leads to a change of resistance depending on the relative orientation of the magnetic layers. Of great interest are also the significant fluctuations of the resistance ($\Delta R \sim 4\%$) observed before the step changes of the resistance took place for both positive and negative currents and especially for 500 $\mu$A step current. This behavior might be attributed to the formation of a vortex-type structure.

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