Publishable JRP Summary Report for EXL04 SpinCal
Spintronics and Spin Caloritronics in Magnetic Nanosystems

Background

The field of spintronics has led both to highest level scientific discoveries and to highly important industrial applications such as hard disk read heads. Here, the controlled propagation and manipulation of individual magnetic domain walls may in the future allow promising applications in data storage and metrology. However, many fundamental questions concerning the controlled domain wall motion in magnetic nanowires need to be answered as a prerequisite for future applications. These questions will be addressed in this project.

Need for the project

Spin-caloritronics has recently emerged from the combination of spintronics and thermo-electricity and focuses on the interaction of electron spins and heat currents. It has led to the observation of fundamentally new effects such as the spin-Seebeck (SSE) effect and thermally induced spin injection. Such novel effects could offer novel device applications for industry and metrology, such as magnetic control of heat flux in a magnetic heat valve. However, to date, many advanced concepts have only a theoretical basis and need to be studied experimentally. Furthermore, this new field requires reliable measurement techniques of spin-caloric properties to underpin future material research.

Several particularly promising device concepts are based on the motion of a magnetic domain wall (DW) in a magnetic nanowire. These could find important industrial applications ranging from high-density lowpower data storage to highly localised field and magnetic moment detection. As a basis for all future device applications, industry requires a fundamental understanding of the device physics and reliable measurement capabilities. This industrial need is explicitly stated in the most recent International Technology Roadmap for Semiconductors (ITRS).

Coupling heat driven transport with spintronics allows new device concepts with promising applications such as innovative spin sources, thermally driven magnetisation reversal by thermal spin transfer torque, magnetic heat valves, or magnetically switchable cooling. However, many of these theoretical concepts are yet to be tested experimentally and there is, therefore, a scientific need to test and validate theoretical predictions to enable future applications. One key problem for the rapidly emerging field of spin-caloritronics is the lack of established methods for reliable measurements of spin-caloritronic material parameters. The SSE effect is one of the most fundamental effects of spin-caloritronics and its discovery in 2008 has boosted worldwide research in the field. The importance of the SSE lies in the fact that it enables efficient generation of spin currents driven by thermal gradients. However, under slightly ill-defined measurement conditions, the SSE can be overlaid (or even dominated) by the spin-Nernst effect, which is not related to spin currents. As a result, the values of the published SSE material parameters are the subject of an on-going and controversial scientific debate.

Scientific and technical objectives

This project addresses fundamental research and enabling metrology for spintronics and spincaloritronics in magnetic nanosystems:

- WP1 will develop measurement schemes and measurement setups to ensure the reliable determination of fundamental spin-caloritronic material parameters.
- WP2 will address open fundamental questions of spin-caloritronics in magnetic nanosystems, such as the magneto-thermopower of an individual domain wall and the magnetic heat valve effect.
- WP3 will focus on fundamental questions of magnetic domain wall propagation in perpendicularly magnetised metallic and semiconducting nanowires.
- WP4 will develop enabling metrology and will explore future paths of metrological applications of magnetic domain wall devices.
- WP5 will focus on the impact of the project by dissemination of the results to scientific and industrial stakeholders worldwide.

Expected results and potential impact

The interaction of basic research and enabling metrology will allow the project objectives to be addressed efficiently and will maximise the impact for the stakeholder community in the field of spintronics and spin-caloritronics. The project participants consist of world leading European researchers from NMIs, universities and research institutes; and will interact with a large number of world leading international collaborators to maximise impact and knowledge transfer.

Guidelines for reliable measurements of SSE material parameters will be drafted and published with the scientific community and will be based on the outcome of an international round robin. The guidelines will represent a first step towards standardisation in this emerging field and will underpin reliable quantitative materials research and development (R&D). Metrology infrastructure for reliable SSE material measurements and metrology tools and methods for the characterisation of spin-caloritronic nano-devices will be established and developed respectively to underpin European based spin-caloritronics research. In addition, metrology infrastructure for the characterisation of the dynamics of DW motion will also be established in response to the requirements of ITRS 2011 for beyond-CMOS metrology. The project will contribute to the fundamental understanding of DW propagation in magnetic nanowires with perpendicular magnetic anisotropy (PMA) and of spin-caloritronics of magnetic nanostructures. New, theoretically proposed spin-caloritronic effects will be quantified experimentally for the first time, and amongst these is the thermo-electrical figure of merit ZT of magnetic tunnel junctions and the field induced modification of heat transport by the magnetic heat valve effect. This will allow an evaluation of the feasibility of future applications such as field-controlled thermo-electrical generators for energy harvesting or fieldcontrolled on-chip heat management. DW devices with PMA will be investigated with respect to sensing and metrology applications and an output of the project is the evaluation of the future prospects of PMA DW devices for metrology and bio-technology applications. Focussed knowledge transfer to the relevant stakeholder groups will be achieved by two Stakeholder Workshops and via direct interaction with existing programmes such as the two DFG Priority Programs on “Spin-Caloric Transport” and on “Semiconductor Spintronics, and with the series of “International Workshops on Spincaloritronics”.

In the first six months, a good collaboration between the project participants and an international Stakeholder Committee were established and various magnetic nanodevices were fabricated by the project participants, including vortex devices, in-plane domain wall devices and perpendicular DW devices. The devices were then shipped to other participants for detailed characterisation. The first measurements of the tunnelling magneto thermo current in an advanced magnetic-tunnel junction (MTJ) system were produced. The magneto-thermoelectric figure of merit of a giant magneto resistive (GMR) spin valve device was also characterised for the first time. Based on these results, the effect of a magnetic field on the efficiency of thermoelectric generators could be evaluated. Here a magnetic field induced change of the efficiency of up to 65% was observed; with the results underpinning future material research on thermoelectric machines based on spin-caloritronic materials.

In the remainder of the first year, the project participants continued their fruitful collaboration with external collaborators from the international Stakeholder Committee. As a key example of collaboration beyond the project, the first round of the round robin comparison experiment on the spin Seebeck effect (SSE) was performed by five international groups (Tohoku University, Ohio State University, Argonne National Laboratory, UBI, INRIM). The initial analysis is ongoing, with further rounds of experiments envisaged, and additional techniques to improve the measurements have been agreed. The SSE comparison results were then presented at the “Dreikönigstreffen” Bad Honnef, international workshop on spin-caloritronics. New magnetic nanodevices were fabricated, including vortex devices, in-plane domain wall devices and perpendicular DW devices; and extensive characterisation has begun. Some measurements of these magnetic nanodevices have already lead to further important results. One of these is the first measurement of the magneto thermo power of an individual magnetic domain wall in a magnetic nanowire, one of the major research goals of the project.

Five groups initially agreed to participate in the SSE round robin experiment, with the international participation (Japan, US, Germany, Italy) expected to guarantee wide acceptance of the results. During the international workshop on spin-caloritronics, two further collaborators decided to participate in the future Round Robin activities of the project, underlining the importance and impact of this project.

The project so far produced four publications in peer-reviewed journals and 11 presentations at international meetings and conferences. Three important presentations given recently include a presentation given by the project coordinator at the EURAMET TC-EM workshop in Paris in January 2014; a presentation to the DFG SpinCal Priority Program Colloquium in February 2014; and an invited presentation, by one of the project researchers, at the Material Research Society (MRS) Spring Meeting in San Franscisco, USA in April 2014. A first three day on-site training in ferromagnetic resonance (FMR) measurements has also been attended by one of the post-doctoral students.

In the third reporting period new research highlights have been obtained. The most recent was the experimental evidence of optical spin torque on a magnetic domain wall (DW). It allows for the first time to manipulate a magnetic DW in semiconductor nanowires using the helicity of absorbed light. It thus provides new tools for the manipulation of DWs beyond magnetic fields and currents. This work lead by REG(FZU) has recently been published in Physical Review Letters.

Another highlight was the first observation of the thermoelectric signature of an individual magnetic DW in a magnetic nanowire. The results well agree with the modelled signature of the anisotropic magneto Seebeck coefficient of permalloy in combination with the nanoscale spin configuration of the DW. This represents the first fundamental link between nano-scale spin structure and macroscopic thermoelelectric properties. A manuscript entitled “DW magneto Seebeck Effect” has been submitted to Nature Nanotechnology. Furthermore it has been awarded an invited talk at the Intermag Bejing 2015.

Also in the third period joint research between the JRP participants is continuing in various fields. For example Michaela Küpferling of INRIM vistited PTB for one month to carry out variable temperature measurements of vortex gyration. The work was funded by a RMG. In this work the samples were fabricated in Bielefeld, room temperature measurements were initially carried out at INRIM and low temperature measurements were carried out in the cryogenic facilities of PTB. The results show for the first time the influence of temperature on vortex gyration in soft magnetic nanodots. A paper on this work has been submitted for presentation at the ICM Barcelona 2015.

The JRP has obtained a very high visibility in the scientific community of spin-caloritronics: The first results of the Spin Seebeck effect Round Robin have been presented during an invited talk at the international conference “Spincaloritronics VI” in Bad Irsee in July 2014. The first round of the round robin showed a significant deviation of measurement results of different laboratories obtained on the same samples and hence demonstrated that spin-Seebeck measurements of different laboratories are far from being comparable. This has generated a significant awareness of stake holders and end users for metrology and measurement reliability in fundamental research. In the discussions at the conference new groups volunteered to participate in the next rounds of the SSE Round Robin. Additional presentations at by consortium members at this conference underlined the visibility of the JRP in the scientific community. Furthermore another invited presentation has been given by REG(INL) at the SPIE Conference in San Diego in August 2014 where results on spin-caloritronics of magnetic tunnel junctions have been presented.

JRP start date and duration:	01 July 2013, 36 months
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