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

Overview

The field of spintronics has led both to highest level scientific discoveries and to important industrial applications, such as hard disk read heads. More recently research has looked at the potential of manipulation of individual magnetic domain walls and the combination of spintronics with thermo-electricity, known as spin caloritronics. The commercialisation of these new technologies requires the development of underpinning metrological infrastructure. This project characterised domain wall devices and developed reliable measurements both for domain wall devices and for spin caloritonics in magnetic nanosystems.

Need for the project

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 low-power 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), a set of documents produced by industrial experts.

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 new effects such as the spin-Seebeck (SSE) effect and thermally induced spin injection. 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. It enables efficient generation of spin currents driven by thermal gradients. However measurements are affected by test conditions and published SSE material parameters are the subject of an on-going and controversial scientific debate. Such novel effects could offer novel device applications for industry and metrology, such as magnetic control of heat flux in a magnetic heat valve.

The rapidly emerging field of spin-caloritronics has a lack of established methods for reliable measurements of spin-caloritronic material parameters which are necessary to underpin future material research.

Scientific and technical objectives

This project addresses fundamental research and enabling metrology for domain wall devices and spin-caloritronics with the following objectives:

1. To develop, realise, and investigate magnetic nanodevices allowing the detection, manipulation, and control of individual magnetic domain walls in advanced magnetic materials with perpendicular magnetic anisotropy (PMA).
2. To develop, realise, and investigate new functional magnetic nanodevices exploiting the interplay of spin-polarised transport and thermal gradients.

The project includes both basic research and enabling metrology to achieve the project objectives efficiently, and to maximise the impact for the stakeholder community in the field of spintronics and spin-caloritronics.

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Results

Investigations of magnetic domain wall nanodevices with perpendicular magnetic anisotropy

Various magnetic nanodevices, including perpendicular DW devices, were fabricated and subject to extensive and detailed characterisation. The metrology infrastructure for the characterisation of perpendicular DW devices was also established.

Experimental evidence of optical spin torque on a magnetic DW with perpendicular magnetic anisotropy was established. It allowed, for the first time, manipulation of a magnetic DW in semiconductor nanowires using the helicity of absorbed light, and thus provided new tools for the manipulation of DWs beyond magnetic fields and currents.

Collaboration between the project partners led to the optimisation of the nano-fabrication process of magnetic domain wall nanodevices with perpendicular magnetic anisotropy. A large number of optimised samples were produced, which were used for experiments on DW based bead detection. Furthermore a new tool for electrical measurements of DW propagation was developed.

The new measurement tool for electrical measurements of DW propagation was thoroughly characterised, and found to be highly versatile and suitable for characterisation of DW dynamics over a broad temperature range. In addition first tests of the detection of magnetic beads by magnetic DW devices have been successfully carried out.

A new thermoelectrical tool for detection of DW propagation has been thoroughly investigated. Room temperature measurements on nanowires with perpendicular magnetic anisotropy have revealed nano-scale resolution below 20 nm of the DW position in a 6 µm long wire. These findings are promising for future studies of field and current induced DW propagation.

In summary, the objective was completed and the metrology for domain wall devices has been established so that complete characterisation of domain wall devices is possible.

Investigations of new functional magnetic nanodevices exploiting the interplay of spin-polarised transport and thermal gradients

Magnetic nanodevices, including vortex devices and in-plane DW devices, were fabricated by the project partners, and underwent detailed characterisation. The first measurements of the tunnelling magneto thermo current in an advanced magnetic-tunnel junction (MTJ) system were produced.

While the magneto resistance of GMR devices has been thoroughly characterised over the last few years the thermo electrical properties have rarely been addressed. The thermo electrical efficiency is one of the key material parameters for all thermo electrical applications, but had never been determined for GMR samples. The project characterised the efficiency of thermo electrical power generation in spintronic devices for the first time. It was found that the thermo electrical efficiency can be changed by more than 60% upon magnetisation reversal. This could prove promising for future thermo electrical applications and machines based on spin-caloritronic materials, for example it allows an external control of thermo electrical devices by the application of a magnetic field.

At the start of the project, there was poor reproducibility of the Spin-Seebeck Coefficient (the measured voltage divided by a geometric factor and the temperature gradient across the ferromagnet). A 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). This resulted in a new method that uses the heat flow instead of the temperature gradient as the external variable. This method has been successfully established and now guarantees a good reproducibility of the Spin-Seebeck coefficients.

Further work was carried out on the fabrication and characterisation of samples. The project:

- Established the first fundamental link between nano-scale spin structure and macroscopic thermoelelectric properties.
- Showed, for the first time, the influence of temperature on vortex gyration in soft magnetic nanodots.
- Performed the first measurements of modification of precessional magnetisation dynamics in magnetic tunnel junctions (MTJs) in the presence of thermal gradients

- Showed that under the influence of local laser heating a significant change of the coercive field was observed showing a similar signature as electrical spin torque
- Demonstrated that the tunnelling magneto resistance (TMR) in MTJ cells can act as a local nano-scale thermometer with high temporal resolution

These results have increased the understanding of spin caloritronics, and highlighted the potential of these properties. It has also helped prepare the metrological infrastructure for these materials.

Actual and potential impact

One of the key aims of the project was to take the first steps towards European and international standardisation by establishing metrology infrastructure for spintronics and spin-caloritronics. The project enabled the metrology infrastructure to be put into place for characterising domain wall devices.

A suitable magneto transport metrology infrastructure is available at NPL and accessible for stakeholder measurements. The fundamental research has meant that reliable measurement and comparisons of spin-caloritonics is now possible. To this extent metrology infrastructure for the reliable measurement of SSE coefficients has been established at INRIM and is accessible for stakeholders. Furthermore a best practice for SSE measurements has been developed and published in an open access journal publication. This will support ongoing research into these materials and underpin quantitative materials research.

Liaising with IEC TC 113 Nanotechnologies has led to a new work item for standardisation of nanoscale magnetic field measurements that is being developed in more detail in a subsequent EURAMET project 16SIB06 NanoMag. These standardisation activities will underpin the reliability of nanoscale magnetic field measurements to improve various industrial applications, like magnetic sensors and actuators, and benefit European industry and R&D centres.

Dissemination of results

Focused knowledge transfer to the relevant stakeholder groups was achieved by workshops in collaboration with existing programmes such as the two programmes in Germany on “Spin-Caloric Transport” and on “Semiconductor Spintronics”, and with the series of “International Workshops on Spin-caloritronics”.

A stakeholder committee of organisations active in the fields of spintronics and spin-caloritronics was set up to clarify the needs of the various interested parties and to feed these into the project. A project website was also set up to keep interested parties up-to-date with key results, publications, etc. and to act as a platform for knowledge exchange with the stakeholder community.

The first SSE comparison results were presented at the “Dreikönigstreffen” Bad Honnef international workshop on spin-caloritronics. This resulted in additional collaborators for the round-robin activities of the project, underlining the importance and impact of the project. These results were then presented again during an invited talk at the international conference “Spincaloritronics VI” in Bad Irsee in July 2014, generating significant awareness by the stakeholders and end users for metrology and measurement reliability in fundamental research.

The project produced 32 publications in peer-reviewed journals and 66 presentations at international meetings and conferences. Further invited presentations were given at Spin-Caloritronics VII in Utrecht and at EMSA 2016 in Torino. During the duration of the project, two training courses/workshops were held for external audiences In Germany, including additional lectures.

Potential impact

The fundamental research carried out within the project will enable European industrial stakeholders to develop more energy efficient ICT devices (e.g. low power magnetic logic and storage devices) and more sensitive diagnostic tools for bio-sensing and manipulation of individual biomolecules (e.g. perpendicular magnetic anisotropy DW sensors). Among the stakeholders potentially benefitting from this project are companies active in advanced instrumentation e.g. for studying DW devices like Durham Magneto Optics, or those active in fundamental spintronics research like the Hitachi Cambridge Research Laboratory.

List of publications

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