FINAL PUBLISHABLE JRP REPORT

JRP-Contract number	EXL04	
JRP short name	SpinCal	
JRP full title	Spintronics and Spin-Caloritronics in Magnetic Nanosystems	
Version numbers of latest contracted Annex Ia and Annex Ib against which the assessment will be made	Annex Ia: V1.0 Annex Ib: V1.0	
Period covered (dates)	From 01 July 2013	To 30 June 2016
JRP-Coordinator		
Name, title, organisation	Hans Werner Schumacher, Dr, PTB	
Tel:	+49 531 592 2500	
Email:	hans.w.schumacher@ptb.de	
JRP website address	http://www.ptb.de/emrp/spincal.html	
Other JRP-Partners		
Short name, country	PTB, Germany INRIM, Italy NPL, UK	
REG1-Researcher (associated Home Organisation)	Jörg Wunderlich FZU, Czech Republic	Start date: 01.07.13 Duration: 36 months
REG2-Researcher (associated Home Organisation)	Tim Böhnert INL, Portugal	Start date: 01.01.14 Duration: 24 months
REG3-Researcher (associated Home Organisation)	Russell Cowburn UCAM, UK	Start date: 01.07.13 Duration: 36 months
REG4-Researcher (associated Home Organisation)	Günter Reiss UBI, Germany	Start date: 01.07.13 Duration: 36 months
REG5-Researcher (associated Home Organisation)	Tim Böhnert INL, Portugal	Start date: 01.01.14 Duration: 30 months
RMG1-Researcher (associated Home Organisation)	Michaela Kuepferling INRIM, Italy	Start date: 01.11.14 Duration: 2 months
RMG2-Researcher (associated Home Organisation)	James Wells NPL, UK	Start date: 01.02.15 Duration: 2 months

Report Status: PU Public

European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

RMG3-Researcher (associated Home Organisation)	Patryk Krzysteczko PTB, Germany	Start date: 01.02.16 Duration: 1 month
ESRMG2-Researcher (associated Home Organisation)	Ambra Caprile INRIM, Italy	Start date: 01.04.15 Duration: 3 months

TABLE OF CONTENTS

1 Executive Summary

Introduction

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 caloritronics in magnetic nanosystems.

The Problem

Several particularly promising device concepts are based on the motion of a magnetic domain wall (DW) in a magnetic nanowire. These could find industrial applications ranging from high-density low-power data storage to highly localised field and magnetic moment detection. To enable development of these devices a fundamental understanding of the device physics and reliable measurement capabilities is required.

Additionally 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.

The Solution

In response to the above problems the SpinCal project has provided new metrology tools and methods for the characterisation of DW devices and spin-caloritronic materials and devices. Specifically:

- a new all-electrical measurement scheme has been developed that allows measurement of the position of a DW in a magnetic nanowire with a few nanometres resolution;
- European metrology infrastructure for the characterisation of DW devices has been established;
- reliable measurement schemes for the quantitative characterisation of spin-caloritronic key material properties have been developed and a European measurement infrastructure has been established;
- first steps towards standardisation of spin-caloritronic key material properties have been taken by drafting guidelines for Spin-Seebeck measurements, and by developing a new measurement method that guarantees a good reproducibility of the Spin-Seebeck coefficients.

Impact

The results obtained represent important steps to underpin European research in promising fields of applied science and thus to strengthen Europe in global R&D competition.

- European industrial stakeholders will be able 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).
- The development of a new high resolution measurement tool for DW propagation will significantly speed up development of DW devices thereby enabling the faster development of new spintronics products for the international market.
- The availability of guidelines will allow for the provision of traceable measurements and for a European and international comparability of material measurements to the benefit of European and international R&D.
- The new robust metrology infrastructure has the capability to underpin appropriate policies and encourage the application of spintronics-based high tech applications, and represents the first steps towards European and International standardisation in the developing fields of spintronics and spin-caloritronics.

2 Project context, rationale and objectives

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. To answer these questions requires reliable metrology tools and methods for the characterisation of DW devices.

Spin-caloritronics has recently emerged from the combination of spintronics and thermo-electricity and it 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 effect (SSE) 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-caloritronic properties to underpin future materials research and applications.

Need for the project

High level European fundamental research in spintronics (the Nobel Prize 2007 was awarded to two European researchers for the discovery of the giant magneto resistance) has led to important industrial and metrological applications such as high density data storage devices and automotive sensors. Spintronics is thus a model for the strong impact of fundamental research on industry and the economy. Today novel and innovative concepts such as spin-caloritronics are emerging, allowing radically new device applications with high economic prospects and the importance of this research has been underlined in FP7[i] being “at the very core of the knowledge-based society”.

Promising device concepts are based on the motion of a magnetic DW in a magnetic nanowire with perpendicular magnetic anisotropy. These could find applications ranging from high-density data storage to nano scale magnetic sensors for bio-tech and health applications. As a basis for all future applications, industry requires reliable measurement capabilities as underlined in the International Technology Roadmap for Semiconductors (ITRS)[ii]. Here the “*dynamics of domain wall motion*” is explicitly listed as one of the “*…specific challenges for spin materials that need advanced characterisation…*”

More recently a new branch of spintronics has evolved called spin-caloritronics, being a combination of thermo-electricity and spintronics. Coupling heat driven transport with spintronics allows new device concepts with promising applications such as innovative spin sources, or more efficient heat thermoelectric generators. 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 and to develop metrology tools and methods for reliable measurements to enable future applications.

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.

3 Research results

In the following the research which was carried out to address the two objectives will be described in more detail. Due to the explorative nature of the project within the "fundamental" EMRP Call, some of the research explicitly addressed fundamental questions, such as the thermoelectrical properties of a single DW in a magnetic nanowire, while other aspects of the research addressed an increase in the reliability of measurements in the field of spin-caloritronics or DW devices.

3.1 Objective 1: Magnetic nanodevices allowing the detection, manipulation, and control of individual magnetic domain walls

3.1.1 Development of a new tool for thermo-electrical detection of DW propagation with nanometer resolution

The demonstration of domain wall (DW) detection with below 20 nm spatial resolution using the anomalous Nernst effect (ANE) is a large step beyond the state of the art. Prior methods for DW nano scale detection were either slow, complex, or invasive. The new thermo-electrical detection technique allows easily accessible and fast all-electrical measurement of the DW propagation in PMA micro and nanowires. This technique will enable new studies on dynamic properties of DW propagation in these highly relevant materials stimulating developments of new sensor and memory device concepts.

This work has been achieved in collaboration of the four project partners PTB, NPL, UCAM, and FZU. Only this collaboration making use of the unique facilities and capabilities of the different partners allowed accomplishment of this major achievement. Among the different techniques and capabilities that were required in this collaboration were the growth of high quality PMA thin films (UCAM), patterning of PMA thin films by electron beam lithography (PTB), development of highly sensitive thermoelectrical measurement setups (PTB), MFM DW manipulation with in-situ magneto-transport (NPL), as well as cryogenic transport measurements in combination with optical Kerr microscopy.

Recent concepts for high-density memory, logic, and sensor devices rely on the controlled positioning and propagation of narrow magnetic domain walls (DW) in nanowires with perpendicular magnetic anisotropy (PMA). To study and develop such systems requires a reliable high-resolution tool for detecting the DW position inside the wire. While magneto-optical microscopy is limited in spatial resolution, high-resolution imaging such as spin resolved electron microscopy, nanomagnetometry, or magnetic force microscopy (MFM) can be complex, time consuming and, for MFM, invasive. The anomalous Hall effect (AHE) allows to probe the position and motion of a DW inside a PMA Hall cross with nanometer resolution however the DW position inside the PMA wire itself is not accessible. Other electrical measurements like giant magneto resistance detection can only be applied on specific spin valve nanowires. Over the last years, the field of spin-caloritonics has explored the interplay of heat and spin currents in spintronic materials and devices. At the same time the anomalous Nernst effect (ANE) moved into focus from being part of careful analysis of spin-caloritronic measurements to detection of magnetisation reversal and magnetisation dynamics in magnetic thin films.

In this work it was shown that ANE provides a powerful tool to detect DW propagation in magnetic nanowires with nano scale resolution. Using a simple thermoelectrical measurement setup allows the probing of current induced, magnetic field induced, and MFM induced DW propagation as well as DW depinning from individual nano scale pinning sites. To highlight the generic character of this method, it was applied to two distinct ferromagnetic PMA systems, namely: metallic Pt/CoFeB/Pt wires with high Curie temperature, and wires patterned from a (GaMn)(AsP)magnetic semiconductor film with Curie temperature below room temperature. DW position detection with spatial resolution down to 20 nm comparable to the DW width in typical PMA materials has been demonstrated.

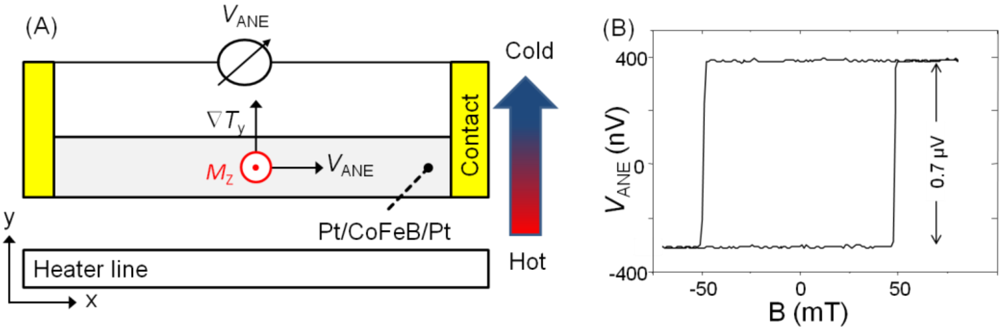

Fig1. (A) Electrical setup for measurement of DW displacement. An in-plane thermal gradient ∇T_y (arrow) is generated using a heater line. The PMA magnetic wire (e.g. of Pt/CoFeB/Pt) has magnetisation M_Z perpendicular to ∇T_y. operated at an ac frequency f. The resulting ANE voltage V_{ANE} can be detected at the wire ends and depends on the orientation of the magnetisation. Full magnetisation reversal measured by ANE is shown in (B). For magnetisation reversal by motion of a single DW the ANE signal is proportional to the position of the DW inside the wire.

Fig 1 shows the geometry allowing DW detection by ANE. In this geometry the thermal gradient ∇T_y, the wires PMA magnetisation Mz and the ANE voltage probes are all oriented perpendicular to each other allowing ANE detection of magnetisation reversal. A typical ANE signal for full magnetisation reversal of the wire is shown in (B). If a single DW moves along the wire during magnetisation reversal the normalised ANE signal is proportional to the position of the DW inside the wire. This fact can be used to detect the movement of an individual magnetic DW with high resolution. In our work we have demonstrated a spatial resolution down to 20 nm which is comparable to the width of the DW in typical PMA materials. This easily accessible high resolution metrology tool will allow a variety of future applications and will foster research and development of DW sensors and devices.

Note that the development of this method had not been part of the initial planning of the project. It has been developed within the project based on the fruitful collaboration of the different partners and based on the joint competences present in the consortium. This allowed us to use a method developed for the detection of the DW thermopower from Objective 2 and modify it for use within Objective 1. Therefore these results are an excellent example of the added value a joint collaborative research can offer over research done by individual partners alone.

3.1.2 Infrastructure for DW device characterisation

A metrological setup for the characterisation of DW devices has been established at NPL. It allows magneto transport measurements in vector magnetic fields over a broad temperature range. The metrological setup has been extensively validated by measurements of NPL in collaboration with REG(UCAM) in the following types of experimental measurements, involving DW dynamics in different systems and experimental conditions, i.e. angular measurements (space state), samples with no notches, new bead types, multilayer CoFeB and Co/Pd devices, test of tapered ends and OLE, MMR measurements. The new setup is highly reliable and provides highly accurate and reproducible measurements. This setup was used for the characterisation of DW devices and DW sensors as described in the following.

<u>Measurements of DW propagation in PMA systems</u>

Within the project a significant effort has been undertaken by the SpinCal partners NPL, UBI, UCAM and INRIM in order to probe the possibility of steady DW motion within nanostructures formed from magnetic materials exhibiting perpendicular anisotropy (PMA).

The work undertaken can be subdivided into the study of stacks made of 1) well-known PMA materials exhibiting high Gilbert damping constants and 2) comparatively new materials engineered in order to exhibit low Gilbert damping. In the case of high damping materials, complementary modelling work has been undertaken in an attempt to simulate DW propagation within nanowires formed from these materials.

A number of key factors are necessary in order for DW devices to be realised within a particular material:

- Low-energy, reproducible injection must be achieved at a specific point within the structure.

- It should then be possible to move the DW in a controlled manner through the structure, preferably between pinning sites at specifically engineered locations.
- Finally, a non-disruptive read-out method is required in order to chart the passage of DWs through the structure.

The PMA material samples delivered by the SpinCal project partners at the universities of Cambridge and Bielefeld were as follows:

<u>DW propagation in devices based on high damping materials</u>

Pt/CoFeB/Pt

UCAM have produced a variety of PMA films incorporating one or more layers of ultra-thin $Co_{60}Fe_{20}B_{20}$ sandwiched between thin platinum spacers. Each PMA stack is fabricated on a substrate of oxidised silicon. Adhesion to the substrate is ensured via the use of a thin layer of tantalum. The resulting films have been patterned into a number of different nanostructures and several distinct experiments have been undertaken. Nanofabrication was initially undertaken at UCAM but has recently been relocated to the clean room at PTB, which has produced a significant improvement in the yield of working devices. A number of experiments have been conducted in order to investigate methods for injecting, pinning and measuring the location of DWs within CoFeB/Pt nanowires.

One or more sample sets using each of the following PMA stacks have been investigated during the SpinCal project to date:

- Single layer CoFeB(0.6nm), CoFeB(0.8nm) and CoFeB(1.3nm)
- CoFeB(0.8nm) bilayer devices, i.e. [CoFeB]2
- (CoFeB(0.6)/Pt)x4 devices for bead sensing, i.e. [CoFeB]4
- *DW Nucleation*

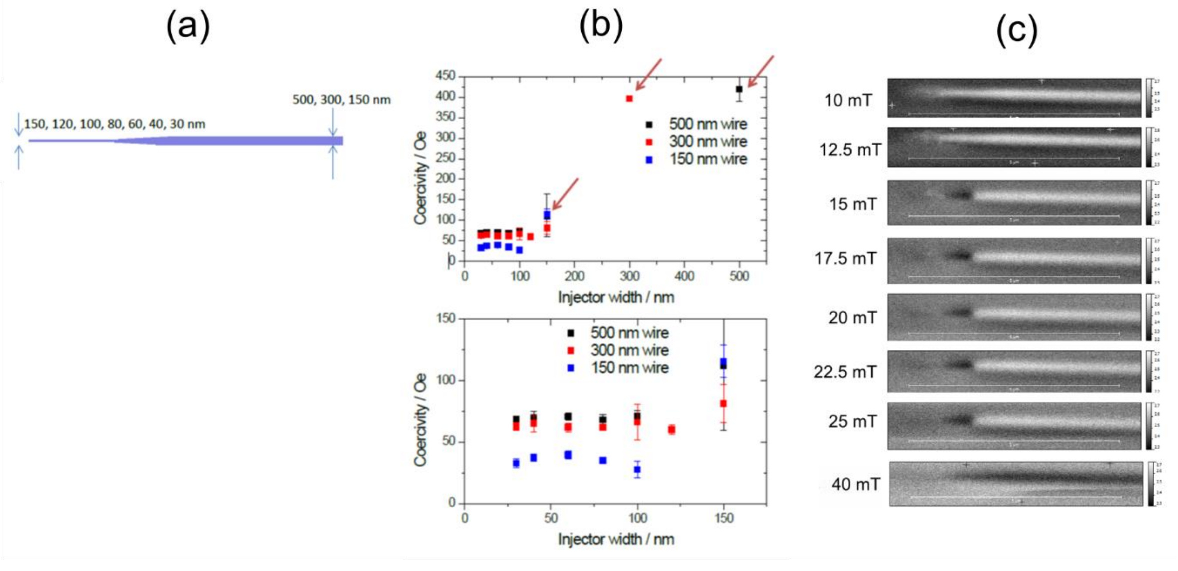

Figure 3 nucleation studies of DW injection using tapered ends on PMA nanowires. Column (a) tapered end geometry and widths studied. (b) coercivietes at tapered end as measured using MOKE microscopy. (c) MFM of low-field DW nucleation occurring at a tapered end in a CoFeB/Pt nanowire. The MFM images show one of the issues preventing smooth DW propagation. In this case, the DW has become pinned until a relatively high field of 40 mT, preventing the observation of smooth, low-field propagation within the wire. Slight variations in the wire geometry and edge roughness between different fabrication sets is the likely cause for the observation of this behaviour in some, but not all devices measured.

MOKE microscopy was used to establish that a reduction in coercivity accompanies a reduction in the width of a CoFeB wire tapered end. This reduction of coercivity may be used to reproducibly inject a DW into the bulk wire under the application of an external out-of-plane field.

FIB irradiation was also investigated as a method of reducing the anisotropy within a small section of a CoFeB wire, so that it might act as a nucleation site for DWs under the application of an external applied field. While some evidence was observed to indicate the creation of reduced nucleation fields at the irradiated locations, the control over the irradiation doses and dose profiles was found to be insufficient in order to achieve reproducible results. As a result, the comparatively simple and reproducible injection offered by tapered ends on nanowires was implemented within the project.

<u>*DW Pinning:*</u> MOKE microscopy was also used to study potential methods for pinning a DW within a CoFeB nanowire after low-field injection at a tapered ends. The pinning effect of a variety of geometrical distortions was examined. Results indicated that, while significant depinning field amplitude and reproducibility was attainable, the majority of pinning geometries had a negligible effect. Observation of DW pinning at notches in nanowires is dependent upon the propagation field within the rest of the PMA nanowire being lower than this pinning field. If too many defects exist within the magnetic wire, then the pinning effect of the notch may be masked by the high-density pinning events throughout the wire.

For straight wires with no Hall crosses or pinning sites, it was observed that DW motion becomes smoother in thinner wires. The likely cause for this behaviour is that the thinner wires have a smaller surface area and therefore the probability of defects occurring is reduced.

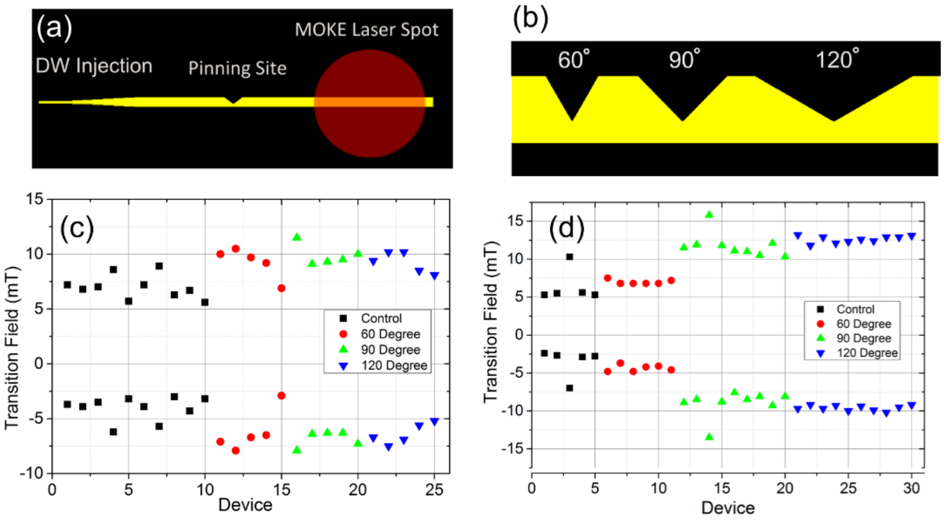

Figure 4 (a) Diagram showing MOKE method for measurement of pinning potentials at notches in PMA nanowires. (b) schematic of notch types studied; (c) depinning fields obtained for 400 nm deep notches in 600 nm wide wires; (d) depinning fields for 200 nm deep notches in 300 nm wide wires.

<u>*Measurement of DW propagation:*</u> A number of electrical read-out methods have been successfully demonstrated within the SpinCal project. These are divided into longitudinal magnetoresistance measurements, transverse measurements of the anomalous Hall Effect and caloritronic measurements based upon voltages resulting from the anomalous Nernst effect in the presence of a thermal gradient.

<u>Longitudinal measurements:</u> 4 probe magnetoresistance measurements have been demonstrated as a possible method to chart the magnetisation reversal process along a length of a PMA wire. In our measurements, we have found that, while the MMR signal is negligible within PMA stacks containing a single layer of CoFeB, within stacks containing two or more CoFeB layers ([CoFeB]2 and [CoFeB]4) it is possible to detect a signal from the magnetisation switching. Conversely, it is also noted that the density of pinning sites within the PMA nanowires increases dramatically within [CoFeB]2 - [CoFeB]4 stacks.

<u>Transverse measurements:</u> The anomalous Hall effect is a well-documented method for measuring the local magnetisation within PMA structures. Hall crosses were initially fabricated from CoFeB films and shown to provide clear magnetisation reversal signals. Steps within the hysteresis loops of these Hall crosses indicated DWs stochastic pinning at the cross junctions. The large variation in the depinning fields from these junctions meant that the Hall crosses were not suitable for use as pinning sites as the reproducibility of depinning from notches was significantly greater. In order to reduce the obstacles to smooth DW propagation within the PMA wires, a new geometry was conceived. A continuous overlying electrode made from non-magnetic material was deposited over the PMA nanowire. A reduced amplitude signal from the AHE was still

measurable, while the obvious advantage of the non-magnetic overlying lead is such that measurement of the local magnetisation could be conducted without interrupting the smooth passage of DWs through the device.

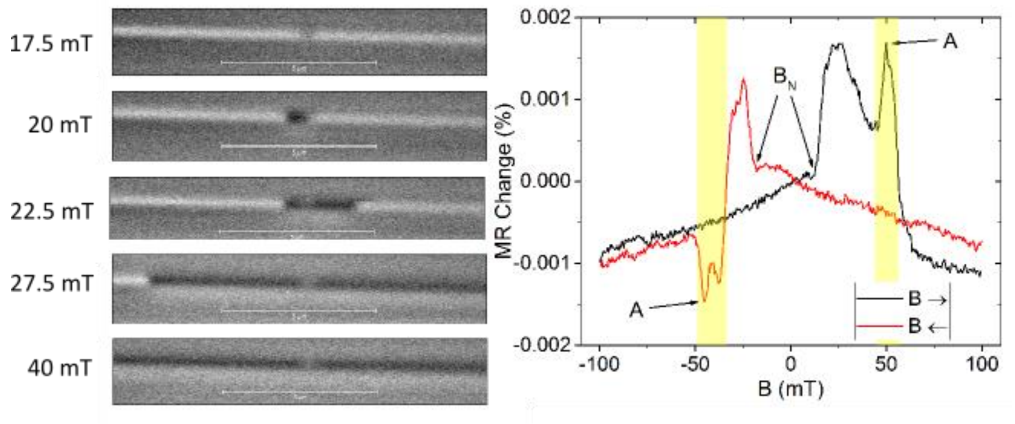

Figure 5. (Left) In situ MFM images showing two domain walls nucleating from a notch within a $[CoFeB]_4$ nanowire. (Right) Longitudinal resistance measurement of the [CoFeB]4 wire. The complex hysteresis curves are related to the propagation of multiple DWs through the device. The feature labelled B_N marks the DW nucleation.

Thermopower measurements: The anomalous Nernst effect has been demonstrated as a powerful tool for measuring the passage of DWs through PMA nanowires as described above. This measurement has a great potential for device development as it offers high-resolution imaging of DW position along the nanowire, while also avoiding the need to pass current through the magnetic element. Current-based degradation of the magnetic stack may therefore be avoided using this technique.

Co/Pd Samples

UBI has delivered a number of nanostructure samples made of different PMA stacks. The stacks have included multiple layers of ultrathin Co sandwiched between Pd spacers.

- $Ta5[Co\ 0.45nm/Pd1.8nm]_9\ MgO_2nm$
- $Ta5[Co0.4Pd1.2]_{12}Ta3Ru3$
- $Ta5[Co0.4Pd1.8]_9Ta3Ru3$

DW Injection and Pinning: No evidence for DW injection or propagation has been observed in any of the measured nanostructures. The use of tapered ends, mechanically induced defects and FIB irradiation have been attempted in an effort to nucleate domain walls within Co/Pd nanowires. A range of geometrical pinning sites (notches, bumps, Hall crosses) has been investigated using both MOKE microscopy and transport measurements. As a conclusion the magnetisation reversal in these sample is dominated by the strong crystalline anisotropy. Therefore a controlled DW injection or nucleation is difficult to achieve hindering direct applications of these materials for DW devices.

Electrical Measurements: The same types of longitudinal (MMR based) and transverse (AHE based) magnetisation monitoring methods described for CoFeB/Pt have been successfully demonstrated within the Co/Pd devices. Signal amplitudes in each case are significantly elevated as comparted to CoFeB/Pt samples. Due to the instantaneous switching of whole devices, which were observed in almost all devices, these measurements have not yet been used to track DW progress through Co/Pd devices.

Co/Pd Prospects: While transport measurements have indicated great potential for measuring the magnetisation of Co/Pd nanostructures, no evidence for steady DW propagation has yet been observed in any of stack types used so far. Without advancement in the fabrication and understanding of the PMA material, the prospect for steady DW motion within this material remains bleak.

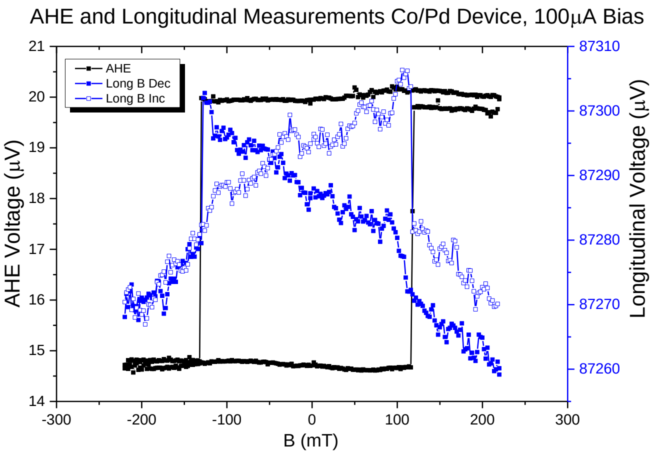

Figure 6. Transverse (black) and longitudinal (blue) electrical hysteresis measurements of a Co/Pd nanowire. A clear signal is seen from the anomalous Hall effect and the magnon magnetoresistance. If DW injection and propagation can be achieved in this material then electrical read-out methods will be a strong tool in device development.

<u>DW propagation in devices based on low damping materials</u>

The magnetisation damping is a defining parameter for the efficiency of spin transfer torque. Therefore one of the planned work within the project was the investigation of DW propagation in nanostructures formed from low-damping materials. Therefore materials and nanowires with varying rations of Mn:Ga were delivered from UBI. The following magnetic component compositions were measured:

- $Mn_{1.6}Ga$
- $Mn_{2.46}Ga$
- $Mn_{2.7}Co_{0.3}Ga$

Unfortunately all of the low damping samples measured were found to exhibit exceptionally high coercivites, which placed great restrictions on their use in developing magnetic nanostructures. In addition to their prohibitively high coercivites, all of the samples measured were found to exhibit magnetisation reversals across a very wide field range. This is consistent with the nucleation of a large number of bubble domains within the wires as opposed to the nucleation and propagation of a single DW through the devices. Due to the high coecivities necessitating the use of a superconducting magnet coil, and the lack of any evidence for single DW nucleation or propagation, the use of low-damping materials within the SpinCal project was terminated at mid term of the project.

Modelling

A significant body of work has been undertaken at INRIM in an attempt to simulate DW nucleation and propagation within PMA nanostructures. Simulations were developed of field-induced DW motion along thin ferromagnetic stripes with high PMA. Two equilibrium states were found depending on the width and thickness of the strip: Bloch DW and Néel DW.

Different aspects have been investigated, such as:

- inclusion of thermal effects via Langevin approach;
- stochastic distribution of anisotropy properties;
- inclusion of randomly distributed defects (e.g., small non-magnetic regions);
- inclusion of Dzyaloshinskii–Moriya interaction.

In spite of the ever increasing level degree of complexity in the simulations, little evidence has yet been observed to support a well-understood steady domain wall motion within the devices.

Evidence is observed for low-field nucleation of domain walls at the tapered ends in the CoFeB/Pt nanowires. Steady DW motion through the wire is not observed, however as in all simulations the DW is seen to pin at the point, at which the nanowire widens from the tapered end. Bubble domain nucleation is then observed throughout the bulk wire at an elevated field (Fig. 7).

Due to the large number of degrees of freedom, it was very difficult to obtain modelling results, which would describe the experimental system fully and adequately. Further information on the main physical parameters and microstructural properties of the PMA film could help to improve the simulations. As found in a number of modelling works, a small variation in the physical parameters might strongly influence the output. This means that knowledge of the real system parameters is of an utmost importance in order to accurately model the system. Unfortunately, the experimental data to date indicates that even nominally identical PMA devices made from identical stacks deposited and patterned using the same recipes can differ greatly in their characteristics.

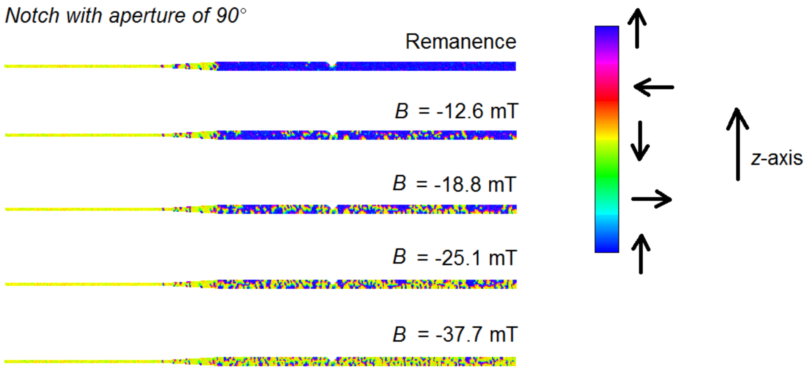

Figure 1 Simulation results for 300 nm wide [CoFeB]$_1$ wire incorporating a tapered end and a notch.

<u>Conclusions</u>: A large and varied number of PMA samples have been investigated during the SpinCal project. At the moment, very limited results have been obtained, which would support steady DW motion within nanostructures. The most promising data has so far been obtained from single layer CoFeB/Pt devices with CoFeB thickness of 0.6 nm. However, even for this material the reproducibility of behaviour between nominally identical sample fabrications remains very poor.

In spite of the issues with long range propagation of DWs in PMA nanowires, the project has recently demonstrated a proof of concept for a DW based magnetic bead sensor. The device implements a direct measurement of the nucleation event at a notch within a nanowire using the AHE and thus circumnavigates the need for smooth DW propagation over long distances or the engineering of pinning sites.

3.1.3 Prospects for DW based magnetic nanosensors:

As described above within SpinCal the prospects for establishing devices based on steady domain wall (DW) motion within magnetic nanostructures exhibiting perpendicular magnetic anisotropy (PMA) were evaluated. Evidence was demonstrated for the injection, propagation and controlled pinning of DWs; primarily within CoFeB/Pt devices.

Previously published results on DW devices suitable for the detection of magnetic beads have employed controlled DW pinning and depinning processes within in-plane magnetised materials. By detecting a modulation of the DW depinning field when a magnetic particle is in close proximity to the device, the presence of the bead may be inferred. The lack of reproducibility in DW propagation and depinning within the PMA materials studied in the SpinCal project meant that MNP detection based on a similar pinning/depinning mechanism within PMA materials was not a realistic outcome within the timeline of the project.

Alternatively, the nucleation and propagation of domain walls within PMA materials have been successfully imaged and electrically measured in CoFeB/Pt devices. Once the issues with stochastic behaviours, unwanted pinning and unsteady DW propagation within CoFeB had been recognised, efforts to implement the nucleation event as the detection mechanism for magnetic particles using PMA materials were undertaken.

In order to implement DW nucleation in a sensor device, a highly reproducible nucleation event must be demonstrated within a structure. An electrical read-out method suitable for detecting the nucleation event is also a requirement. A notch placed within an otherwise uniform PMA nanowire reduces the local anisotropy at that feature, thus producing a highly reproducible nucleation site under applied out-of-plane fields, see Fig. 5.

The details of the initial development of a CoFeB/Pt nucleation based sensor, based on a notched CoFeB/Pt nanowire can be found in publication No. 23. This paper documents the development of a nucleation based sensor where a non-magnetic electrode overlying a notch in a PMA wire is used to monitor the nucleation event at the notch under applied out-of-plane fields. The paper provides an initial demonstration of device functioning by comparing the reversal behaviour of the clean device with that of the device in the presence of a relatively large permanent magnet - NdFeB microbead. A single NdFeB microparticle attached to the apex of an AFM probe is initially held above the sensor junction, and the shift in the device's hysteresis loop is measured. After this, the sensor volume of the device is mapped by scanning the bead across the device surface at varying lift heights, while recording the AHE at each probe position. A small bias field (of opposite polarity to NdFeB bead magnetisation) is applied during measurements in order to ensure that the device magnetisation returns to its original state after the bead has passed. The technique measures the volume, in which the stray field component of the NdFeB particle is sufficient in order to nucleate domain walls within the device junction. DW nucleation as a direct result of the particle's stray field is observed at lift heights up to 800 nm. This is double the distance measured in Py devices using the same type of particle, and represents a significant improvement in device sensitivity when using PMA materials.

Despite being a very significant improvement to the previous works, in terms of real-world applications, the detection of NdFeB particles is of limited interest. These particles are strongly ferromagnetic (i.e. prone to agglomeration due to dipole interaction) and formed from potentially toxic material. For most Life Science studies using magnetic labelling, the particles of choice are formed from iron oxides and exhibit superparamagnetic behaviour. Therefore, after proving the potential of the nucleation sensor, studies moved to attempts to detect iron oxide particles using the technique. AFM probes were prepared with different type of iron oxide nanoparticle fixed at the apex. A range of particle diameters, i.e. 3 micron, 1 micron, 100 nm, were so far studied (Fig. 8).

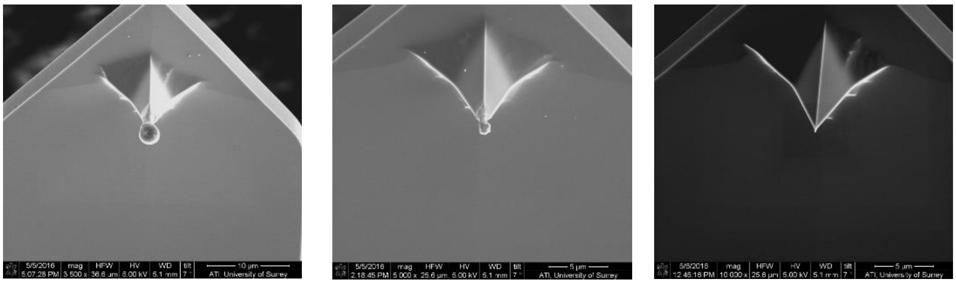

Figure 8: AFM probes tipped with 3 micron, 1 micron and 100 nm diameter iron oxide particles.

Superparamagnetic iron oxide particles exhibit no remanent magnetisation, meaning that without external magnetic field they would be unable to nucleate domain walls within the sensor junction just by passing close to the device. The effect of a stationary particle situated above the sensor junction on the device's hysteresis loop was, however, investigated. Fig. 9 shows a diagram of a sensor junction and its remagnetisation process in the left column (Fig. 9 a – c), with an example of a hysteresis loop of the clean device in (Fig. 9d). Fig. 9h demonstrates a hysteresis loop measured from the same device as in Fig. 9 d, however an iron oxide particle has been placed off-site of the notch, as depicted in Fig. 9e-g. The particle is situated 20 nm above the device. The hysteresis loop in Fig. 9h shows a clear step as a result of the proximity nanoparticle, indicating that the particle has modified the remagnetisation behaviour of one half of the junction. A possible schematic of this behaviour is shown in Fig. 9 a-c.

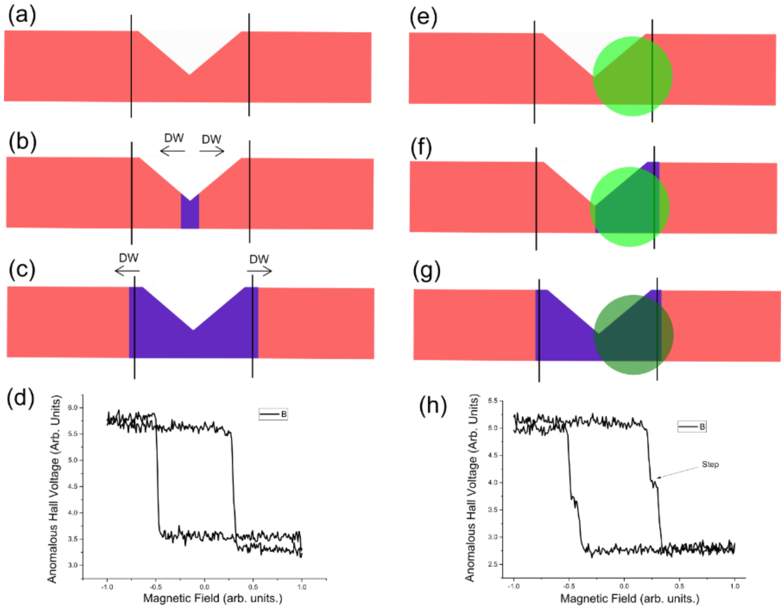

Figure 9. (a-c) schematic of DW nucleation process in a clean device junction; d) AHE hysteresis loop for a clean junction. (e-g) schematic of magnetisation reversal at a device junction in proximity to a MNP; h) AHE hysteresis loop for a device in proximity to a MNP.

Fig. 10 further studies the effect of an iron oxide nanoparticle on a sensor junction. It plots the hysteresis loop transitions in each polarity for a device with a 3 micron iron oxide particle situated above one half of the sensor junction. In each field direction a reduction in the coercivity of one half of the junction is observed in the presence of the particle. The magnitude of the coercivity shift is ~3.6 mT.

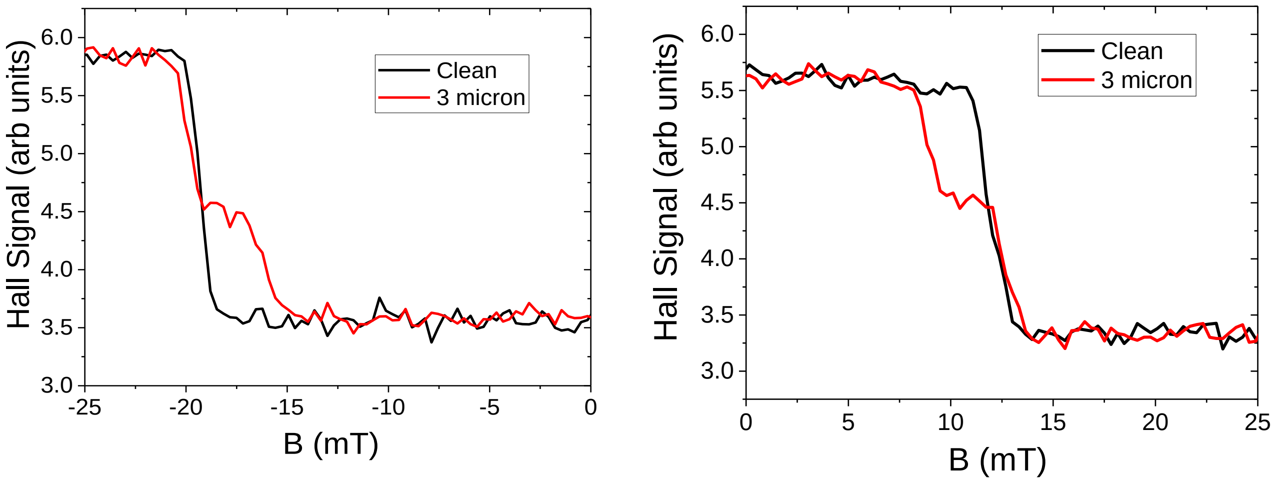

Figure 10. Superpositions of negative (left) and positive (right) transitions in hysteresis loops measured for a clean device and a device in the presence of a 3 micron particle placed to once side of the sensor junction.

In an attempt to understand the results shown in Figs. 9 and 10, a schematic of the proposed remagnetisation process for a junction in the presence of a particle is shown in Fig. 11. The interaction process between the device and particle begins in a saturated state as shown in (a), as the field is increased in the opposite direction the low coercivity of the iron oxide particle causes it to reverse at a lower field than the nucleation field of the clean notch. After the particle has remagnetised, its stray field enhances the local field above one half of the junction. As a result of the contribution from the particle, the nucleation field for one half of the junction is reached at a slightly reduced applied field (c).

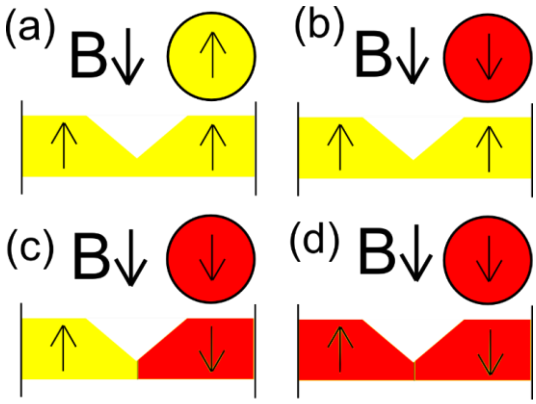

Figure 11: Illustration of a possible mechanism for remagnetisation process of device in presence of a bead.

Having demonstrated a clear signal from the 3 micron iron oxide particles, the 1 micron diameter particles were then investigated. Fig. 12 plots averaged (5 sweep) curves for a clean device, and in the presence of 3 and 1 micron particles positioned off-side the notch. Although the curves are slightly smoothed due to the averaging process, a clear reduction of the switching field is still measureable for the 1 micron particle.

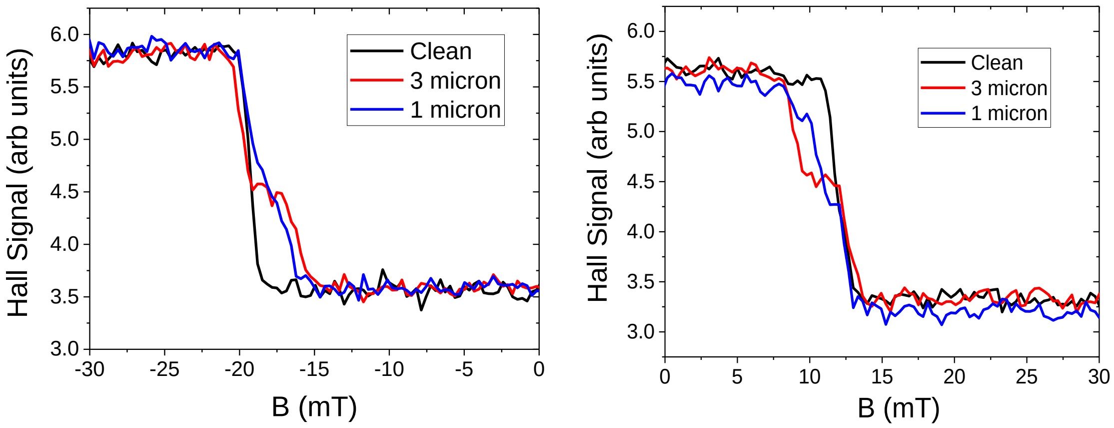

Fig. 12: Effect of 3 micron and 1 micron iron oxide particles on a switching field of the device as compared with the clean hysteresis loop.

The next test of the nucleation sensor was to investigate the bead-sensor separation, at which iron oxide particles could be detected. Fig. 13 shows results for 3 micron, 1 micron and 100 nm (nanoflower, NF) particles at varying distances above a sensor junction. The y axis is the width of the magnetisation reversal in the hysteresis loop. The value marked Z is the width of the transition in a clean device, i.e. a zero reading in this experiment. For 3 micron particles, a significant effect is observed, which is detectable at large bead-sensor separations of more than 600 nm. A less complete data set has so far been obtained for the 1 micron particle, although a reduced amplitude signal is observed which appears to follow a similar decay with separation to the 3 micron. A single data point has so far been obtained for the 100 nm particle. While no step is immediately observable within the data for this particle type, a slight widening of the transition does in fact occur in the presence of the particle. As these results are very interesting and highly applicable, it is intended to carry on with the experimental work outside the frame of SpinCal project, to attain a complete data set for all particle types at all lift heights (until signal extinguished). This is a highly time consuming and delicate process due to the nature of scanning probe imaging, the tendency of the system to drift laterally during the measurement of hysteresis loops, the tendency for particles to disintegrate or fall off probes and the possibility of damage occurring to the sensor device itself after being scanned many times with a probe and carrying current for long periods of time.

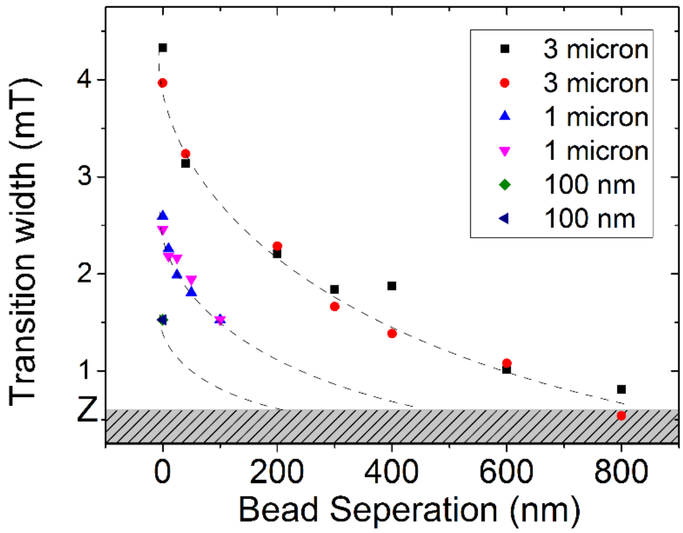

Figure 13. Shift in switching fields of device hysteresis transition for 3 types of iron oxide particles at varying heights above the sensor. Dashed lines show projected relationships for incomplete data sets.

The data so far obtained indicates that the nucleation sensor technique using PMA materials has great potential for the high-sensitivity detection of iron oxide magnetic nanoparticles. Further improvements in sensitivity may be achieved by further variation in the device design, however the demonstrated device is capable of detecting particles with direct interest for diagnostic and immunoassay applications. As a result of this experiment, a collaborative study is planned with the NPL biotechnology group in order to test the effect of functionalisation on the nucleation sensor devices, and to investigate the possibility of using functionalised devices to capture nanoparticles from solution and read-out the captured nanoparticle's presence via electrical means. As such the prospects for detecting magnetic beads using magnetic nanoparticles are very positive, with additional work planned to continue device development in the period after SpinCal ends. The PMA film coercivities, defect densities and magnetoelectrical properties vary greatly between different sputtering depositions. After processing into nanostructures the variation in device behaviours can be significant. Similarly the yield of functioning devices between different fabrications can vary greatly. For example, only the most recent deliveries of samples have shown approximately 80%, 50% and 0% device yields. For DW sensors based on PMA materials to have real commercial prospects, the reproducibility and yield of devices must be addressed.

Conclusions:

Based on the intense collaboration of the project partners various aspects of DW propagation in magnetic nanodevices have been investigated. New metrology infrastructure has been established and new metrology tools have been developed. Using the new tools various aspects of the physical foundation of DW devices have been studied. Based on these results new and promising sensor concepts suitable for the detection of magnetic beads have been developed. These new sensor concepts will be investigated with respect to bio-tech applications in future collaborations of the involved project partners.

3.2 Objective 2: new functional magnetic nanodevices exploiting the interplay of spin-polarised transport and thermal gradients

The research with respect to Objective 2 focussed on two main aspects of the field of spin-caloritronics which will be described in the following:

- Development of reliable measurement tools and methods for measurements of the spin-Seebeck effect
- Measurements of fundamental spin-caloritronic properties of magnetic nanodevices

3.2.1 Reliable spin-Seebeck measurements

The coupling between spin and charge transport in condensed matter is studied in the lively field of spintronics, that could provide extremely low power ultrasmall electronic devices. However, heat currents dissipated in such devices are coupled to both charge and spin currents. Spin caloritronics now additionally combines thermoelectrics with spintronics and nanomagnetism, and offers the possibility to use waste heat for the operation of electronics.

In particular, we concentrated on Spin-Seebeck materials and devices. In the so-called Longitudinal Spin Seebeck Effect (LSSE), a ferromagnetic insulator with magnetisation in the film plane is covered by a thin Platinum layer. When a temperature gradient is applied to this system perpendicular to the film plane, a voltage is generated in the Platinum that can drive, e.g., a current for supplying other devices. The source of the voltage is the Inverse Spin Seebeck Effect that converts a spin current into a charge current.

At the start of SpinCal, however, LSSE measurements suffered from a very poor reproducibility concerning the Spin Seebeck Coefficient (the measured voltage divided by a geometric factor and the temperature gradient across the ferromagnet). We contributed to develop a new method that uses the heat flow (given in Watts per Square-meter) instead of the temperature gradient (given in Kelvin per Meter) as external variable. This method has been successfully established in a worldwide Round Robin experiment and now guarantees a good reproducibility of the Spin Seebeck coefficients that are given in Watts /(Volt Meter).

Experimental setup: Measurements of LSSE voltage are performed by the system represented schematically in Figure 14. The system is a closed thermal circuit in which a given quantity of heat flows through elements that are in series: the thermoelectric elements used as heat flux sensors (c), the sample under investigation (f), and a couple of power Peltier cells (d), used as heat flux actuators. We use two T-type thermocouples (a) for the measurement of the temperature difference between the two brass blocks. We measure the temperature of the heat sink by a standard Pt-100 thermometer (e). The heat sink is connected to the heat flux actuators and is stabilised to room temperature by a cryo-circulator.

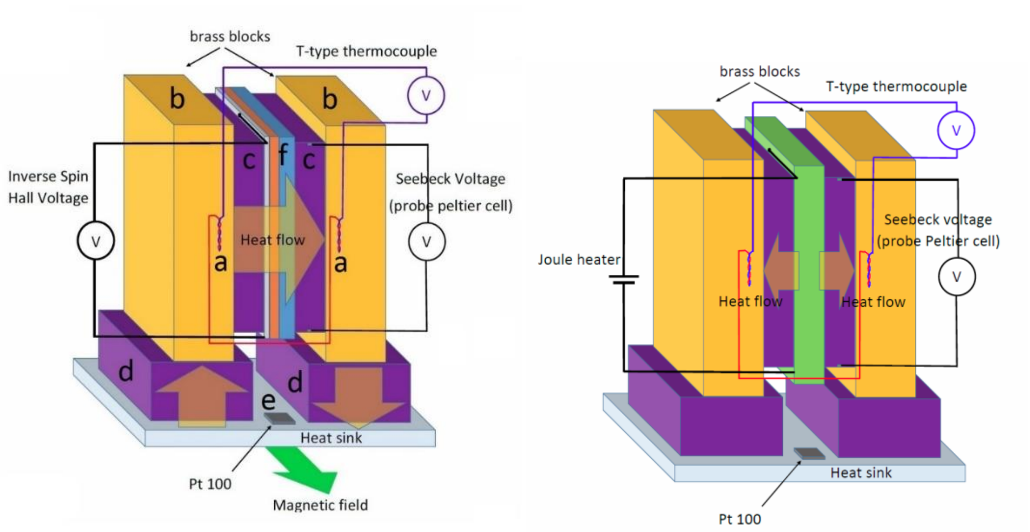

Figure 14: experimental setup for the characterisation of the LSSE as a function of the heat flux

We calibrated the heat flux sensors by using an electric heater resistor as a known Joule heat source placed between the two heat flux sensors, as shown in figure 14.b. The response of the probe peltier as function of the heat flow is reported in figure 15.

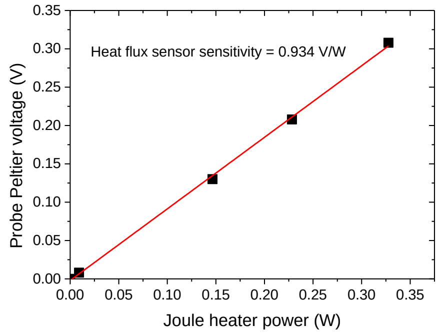

Figure 15. Calibration curve of the probe peltier sensor

Measurement methods: We impose and measure a given heat flux by the aforementioned system and simultaneously we measure the LSSE voltage as the half difference between the voltages at the opposite values of the saturation magnetic field. The values of LSSE voltage (presented in Figure 16.a) are recorded by a keithley 2182a nanovoltmeter. The magnetic field is obtained by an electromagnet and is measured by a Hall probe gaussmeter; it is continuously swept between 70mT and -70mT with a period of 20 minutes. In Figure 16.b are reported values for the LSSE voltage, normalised with the distance of the electric contacts w_{Pt}, as a function of the heat flux for the saturating magnetic field.

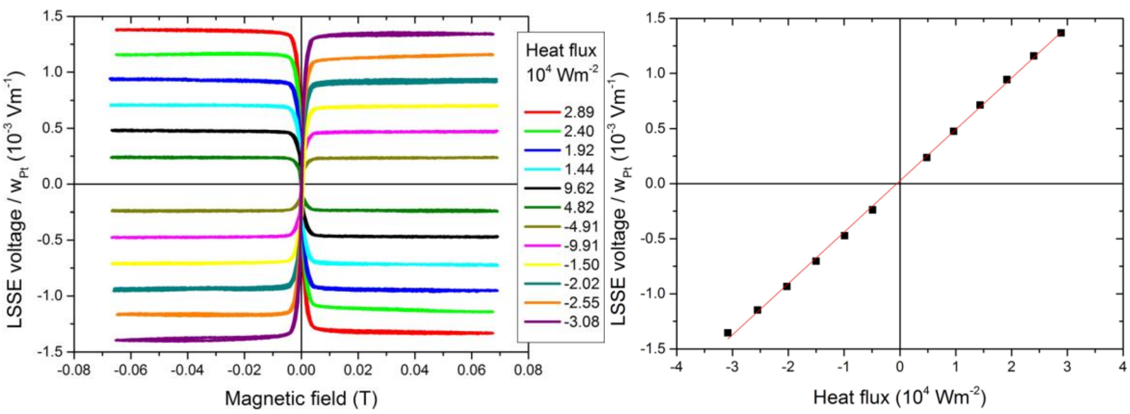

Figure 16. Normalised LSSE voltage at various heat fluxes through the sample

Dependence of LSSE coefficient on the temperature difference: From the linear fit of data reported in Figure 16.b it is possible to obtain the normalised spin Seebeck voltage over the heat flux (characteristic of the sample):

$$\frac{LSSE\ voltage/w_{Pt}}{Heat\ flux} = 4.66 \cdot 10^{-8} VmW^{-1}$$

The related intensive quantity can be obtained by doing some assumption on the value of the thermal conductivity of the YIG layer and by taking in account the dimensions of the sample.

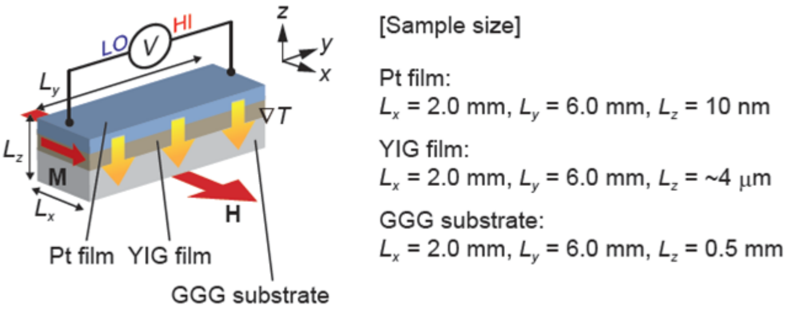

Figure 17. Sample geometry and dimensions

If we assume a thermal conductivity of the YIG layer equal to 6 $Wm^{-1}K^{-1}$, the spin Seebeck coefficient for the YIG in the device under investigation is equal to **$2.8 \cdot 10^{-7}$ V/K**.

This new measurement method developed within SpinCal enables a much more reliable determination of spin-Seebeck material parameters than before. This underpins reliable R&D and material optimisation for future application of spin-caloritionic materials.

3.2.2 Fundamental spin-caloritronic properties of magnetic nanodevices

Within the project a variety of fundamental aspects of spin-caloritronics in magnetic nanodevices have been addressed by the consortium. Among them were the first measurement of the magneto thermo power of an individual magnetic DW, the first measurement of the magneto-thermoelectric figure of merit of a giant magneto resistance (GMR) stack and the first measurement of the tunnel magneto thermo current in a magneto tunnel junction (MTJ) stack. These results will now be described in more detail.

DW thermo power: At PTB a new measurement infrastructure has been developed allowing measurement of the magneto thermo electric properties of magnetic nano devices at room temperature and in a cryogenic environment over the temperature range from 1.5 – 300 K in magnetic vector fields up to 1 T. This setup was used for the characterisation of the thermopower contribution of an individual magnetic domain wall, among others. This setup was also one of the keys to the development of the new DW detection tool described with respect to Objective 1.

To measure the thermopower of an individual DW, first DW devices were fabricated from NiFe thin film which allowed controllablenucleation of a DW at a bent of a nanowire and controllable pin the DW at a notch between two electrical contact. Generation of a temperature gradient by an electrical heater allowed measurement of the thermopower of the wire with and without the DW pinned at the notch. In the presence of a pinned DW at the notch a clear signal was found that could be attributed to the anisotropic magneto Seebeck (AMS) signal of an individual magnetic DW as shown in Fig. 18. Other contributions like ANE or planar Nernst effect (PNE) could be ruled out based on simulations.

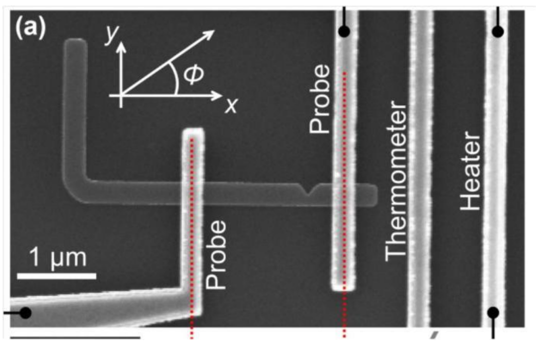

Fig 18. NiFe nanowire for the measurement of DW thermopower with electrical heater lines.

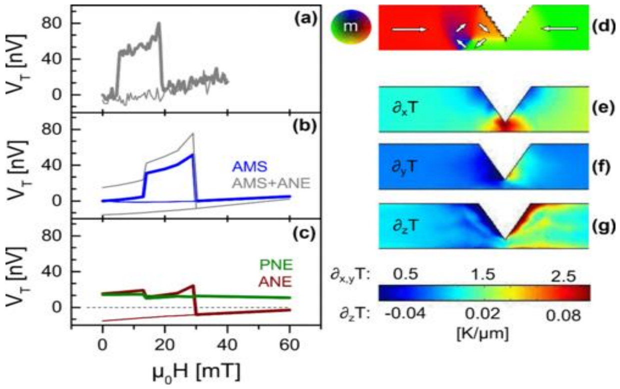

Fig 18. (Taken from publication 21): (a) Domain wall magnetothermopower measured at $\phi=-30^\circ$ (upsweep, thick line; downsweep, thin line). The graph shows the thermopower change with respect to the remanent state. (b) The calculated AMS contribution (blue) and the calculated contribution due to AMS and ANE acting together (gray). (c) Calculated contribution due to PNE (green) and ANE (brown). (d) Example of a simulated magnetization distribution showing a vortex DW. The local magnetisation direction is indicated by the colour scale. (e)–(g) Maps of the calculated temperature gradient in the x,y, and z directions.

This work has been published in Physical Review Rapid Communications (Publication 21) under the label "Editor's Suggestion".

Magneto thermo electrical figure of merit of a GMS stack: In this collaborative work GMR samples have been fabricated at the University of Bielefeld which have been characterised with respect to thermoelectrical properties at PTB.

While the magneto resistance of GMR devices has been thoroughly characterised over the last years the thermo electrical properties have only rarely been addressed. The thermo electrical efficiency ZT is one of the key material parameters for all thermo electrical applications. This key parameter had never been determined for GMR samples before the start of the project. Fig. 19 shows the ZT value determined for a GMR wire as described in publication 3. The data shows that the thermo electrical efficiency can be changed by more than 60% upon magnetisation reversal. This could prove promising for future thermo electrical applications. It could for example allow an external control of thermo electrical devices by the application of a magnetic field.

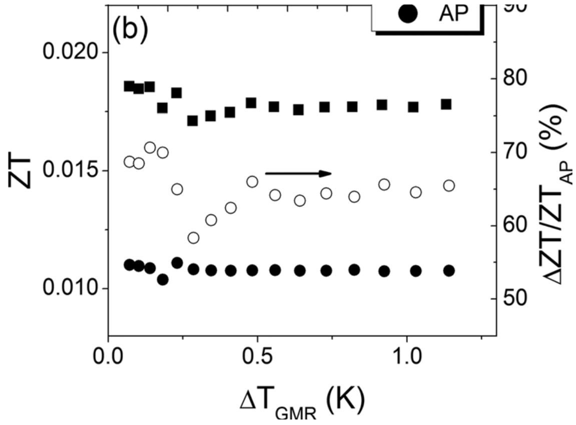

Fig 19. (Taken from publication 3): Thermo electrical efficiency ZT (full symbols) derived from measurements of a GMR wire in the parallel (square) and antiparallel (circle) magnetization state. ZT is measured as function of the applied thermal gradient ΔT. ZT varies on average by more than 60 % upon magnetisation reversal as given by the open dots.

Magneto thermo current of a MTJ nano pillar: This aspect of spin-caloritronics of magnetic nanodevices has been investigated collaboration with the University of Bielefeld (sample fabrication), INL (data analysis) and PTB (measurements and data analysis).

Before the start of the project the tunnelling magneto thermo power (TMTP) had recently been discovered. TMTP stands for the change of the magneto thermo power of an MTJ stack upon magnetisation switching from parallel to antiparallel orientation of the two magnetic layers of the MTJ. When a magneto thermo power is present in an open circuit voltage measurement it should also lead to a magneto thermo current in a short circuit measurement setup. However this so-called tunnelling magneto thermo current (TMTC) could not be experimentally observed. Within the project this TMTC has been measured in a magnetic tunnel junction nanopillar for the first time. As described in publication 1 this effect can reach amplitudes up to 50 % which are in quantitative agreement with the predictions of the Onsager relations for the devices under investigation.

3.3 Summary of Research Results:

A large number of research results have been obtained within the SpinCal project. The key results in bullet form are as follows:

New measurement capabilities

- Infrastructure for the characterisation of DW devices at NPL (unique infrastructure at an NMI)
- Infrastructure for the characterisation of thermoelectrical properties of magnetic nano devices at PTB (unique infrastructure at an NMI)
- Infrastructure for the characterisation of spin-Seebeck parameters using the heat flux method at PTB and UBI (world unique infrastructure)

New procedures developed

- A new method for the thermo-electrical detection of DW propagation
- A new method for controlling the DW propagation in a magnetic nanowire by an MFM tip
- A new method for the reliable measurement of the spin-Seebeck effect based on the heat flux method
- A new method for controlling nucleation in perpendicularly magnetised nanowires through in-plane shape
- A new method for magnetic bead detection based on measurements of the DW nucleation in magnetic nanowires

Key technical insights gained

- First measurement of the magneto thermo power of an individual magnetic DW
- First measurement of the tunnel magneto thermo current of an MTJ stack
- First measurement of the magneto-ZT of a GMR system.
- First measurement of optical spin transfer torque driven domain wall motion
- Characterisation of the microwave absorption properties of GaMnAs and GaMnAsP thin films and devices.
- First realisation of PMA thin film growth on polyimide substrates enabling future applications in flexible electronics
- Realisation of two-dimensional control of field-driven magnetic bubble movement using Dzyaloshinskii–Moriya interactions in PMA thin films
- First determination of the longitudinal spin Seebeck effect contribution in transverse spin Seebeck effect experiments in Pt/YIG and Pt/NFO

4 Actual and potential impact

4.1 Metrology achievements

New metrology tools and methods:

The demonstration of domain wall (DW) detection with below 20 nm spatial resolution using the anomalous Nernst effect (ANE) is a large step beyond the state of the art. Prior methods for DW nano scale detection were either slow, complex, or invasive. The new thermo-electrical detection technique allows easily accessible and fast all-electrical measurement of the DW propagation in PMA micro and nanowires. This technique will enable new studies on dynamical properties of DW propagation in these highly relevant materials stimulating developments of new sensor and memory device concepts.

The project further developed a new sensor type based on DW nucleation in PMA materials. It has a great potential for the high-sensitivity room temperature detection of iron oxide magnetic nanoparticles (with size down to 100 nm). Further improvements in sensitivity could be achieved by further variation in the device design, however already the demonstrated device is capable of detecting particles with direct interest for diagnostic and immunoassay applications. The proof of concept approach for detecting magnetic beads using ultra-thin CoFeB devices is very positive.

The fundamental research has meant that reliable measurement and comparisons of spin-caloritonics is now possible. A new metrology method for the determination of the spin-Seebeck effect (SSE) coefficients has been developed. This new method is based on the determination of the heat flux through the samples instead of the temperature difference across the sample. This approach dramatically reduces the uncertainties resulting from ill-defined thermal contacts at interfaces. The new method has been described in guidelines for reliable SSE measurements. 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.

New metrology infrastructure:

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. New infrastructure for reliable SSE measurements has been established both at INRIM and at UBI. The two measurement setups are based on the newly developed heat flux method and allow reliable calibration of SSE samples from external stakeholders.

New infrastructure for the characterisation of DW devices with PMA has been established at PTB and NPL. At NPL magnetotransport infrastructure as well as MFM imaging tools are available for the characterisation of magnetic DW devices. At PTB measurement setups for the characterisation of the thermoelectrical properties of nano scale DW devices are available.

4.2 Dissemination activities

Scientific publications:

The project has published 32 scientific papers in international scientific journals, among them several high impact publications (e.g. in Physical Review Letters, Nature group, …). Five more manuscripts are presently in preparation. These publications convey the significant scientific outputs of the project. A list is provided in section 6.

Conference contributions:

The project has generated 66 contributions to international scientific conferences. The high quality of the scientific output is underlined by a total of 16 invited presentations.

Contributions have been presented at all relevant key conferences series such as Intermag, MMM, Joint MMM-Intermag, ICM, JEMS, and the Spin-Caloritronics workshop series.

The conference contributions have received a best student presentation award (EMSA 2014), the best poster award (MMM 2016), and one of the PIs was awarded Wolfarth Lecturer.

Patents:

One patent application has been filed and granted.

Stakeholder Engagement

The Stakeholder Committee, consisting of international leading scientists in the field, has been regularly updated on the developments of the project (e.g. via participation in the DFG-SpinCaT Priority Program meeting in Bad Honnef in Feb 2016). The interplay between project Partners and the stakeholder community is the foundation for future standardisation and the development of a European metrology infrastructure for spin-caloritronics. For example, 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 workshop

The project results have been disseminated to the international spincaloritronics community by the final focussed presentations at the Spin Caloritronics VII conference in July 2016 in Utrecht. Two invited talks by speakers from the consortium and a number of poster presentations enabled to efficiently disseminate the project results for the relevant scientific community. The conference has been attended by both the scientific community and stakeholder's active in the field. Therefore it represented an excellent opportunity for focused dissemination of the JRP results.

Increase of public awareness:

The European Researchers' Night is the largest European event devoted to science and research, promoted by the European Commission with the aim of bringing researchers and citizens in contact, to disseminate scientific culture and knowledge about research careers and to offer a wide variety of fun-learning activities in an informal and stimulating context.

The 2016 edition, held on Friday 30 September in more than 200 European cities, was once again a great success. In Italy 52 cities participated in the event, among which Torino, where more than 1000 researchers from Universities, Research Centres and start-up companies were involved to meet the general public. Children and adults got the chance of getting a closer look at the researchers' activities, with hands-on experiments, interactive live tests, dissemination conferences, science theatre performances, behind-the-scenes guided tours of museums and research labs and much more.

With respect to this project, the Partner INRIM presented a hands-on experiment of thermoelectricity highlighting the principle of a thermoelectric generator as well as information on spintronics accessible by the layman.

4.3 Effective cooperation between project Partners

The European Metrology Research Programme (EMRP) is a metrology-focused European programme of coordinated R&D aimed at facilitating closer integration of national research programmes and ensuring collaboration between National Measurement Institutes, reducing duplication and increasing impact.

This project has been a good example of the implementation of this programme, gathering NMIs and academic partners from European Countries with major R&D activities in the field of spintronics and spin-caloritronics.

Collaborative research:

The results of the project reach far beyond what could have been achieved by the activities of a single partner. The basis for the success of the project was an intense collaboration of the consortium partners. This is demonstrated by a total of 17 joint scientific publications that have been published or submitted in the course of the project.

A few examples of such collaborations are listed below:

- Thin film materials for DW devices have been grown by UCAM and UBI. The films have been patterned into DW nanowires by high resolution electron beam lithography in PTB's clean room facility. Thermoelectric characterisation of the patterned DW devices has been carried out at PTB. NPL has investigated the suitability of these devices for DW sensing of magnetic nanoparticles.

- UBI and INL have fabricated magnetic vortex devices by sputter deposition and electron beam lithography and have characterised the static magnetic properties. Characterisation of the dynamic vortex properties have been performed at INRIM. Complementary dynamic measurements of vortex dynamics at variable temperatures have been performed at PTB in a dedicated cryogentic measurement system with high frequency wiring. Detailed theoretical data analysis has been carried out at INRIM.
- A novel measurement scheme enabling the more reliable characterisation of spin-Seebeck material parameters has been devised by INRIM and a first measurement setup has been realised at INRIM. SpinCal internal knowledge transfer enabled the development of a second setup at UBI. By comparison measurements of the properties of reference materials using the two setups at INRIM and UBI the new setup and measurement method was validated yielding a much better reproducibility of measurement results than obtained in the state of the art.

Mobility of researchers:

This project has demonstrated a very high level of transnational mobility and exchange of researchers. This mobility has partly been funded by RMG / ESRMG schemes within EMRP or by internal funds of the partners. Examples for such visits (between one weeks up to six month) for intense on-site collaborations were:

- Two secondments of NPL researchers to PTB for collaboration on thermoelectrical measurements on DW devices and on magnetic sensors.
- A total of five secondments of PTB researchers to NPL, INRIM, FZU, and INL for joint spin-caloritronic measurements.
- Three secondments of INRIM researchers to NPL, PTB, and UBI for joint investigations of spin-caloritronics and DW sensor devices.

4.4 Examples of early impact

Standards

Consortium members have regularly updated the EURAMET Technical Committee for Electricity and Magnetism (TC-EM) on the outcome of the project. A report on the project activities and final achievements has been sent to the TC-EM Chair Dr. Luca Callegaro in July 2016.

The project Coordinator has been appointed project leader for a potential work item (PWI) within the IEC TC 113 Nanotechnologies. This PWI aims for standardisation of nano scale magnetic field measurements which directly benefits from the results of the project.

Adoption of new metrology tools and methods

After presentation of the new measurement procedure for reliable measurements of spin-Seebeck material properties at a scientific conference an international stakeholder group has adopted the new technique in their laboratories. This demonstrates the high impact of the project for international harmonisation of spin-caloritronic measurements.

Uptake

Within the project new sensor concepts based on PMA DW nucleation for magnetic bead detection have been proposed and tested. The further development of these concepts for bio applications will be fostered in a follow up research project by NPL.

4.5 Potential impact

In the long term, this project will support spintronics related ICT R&D by stimulating innovation and will enable new spintronics and spin-caloritronics devices and applications in the European ICT industry. These new developments will also be based on the publications which have submitted and published during this reporting period.

First steps towards standardisation of SSE measurements have been taken by proposing a new and more reliable SSE measurement scheme based on heat flux measurements. Furthermore the project has delivered enabling metrology for the spintronics industry accessible beyond the end of the project.

The coordinator and partners have liaised with stakeholders from the spin-caloritronics community to raise awareness for reliability problems of SSE measurement and were asked to contribute to a best practise guide for SSE measurements, which will generate impact beyond the end of the project.

The fundamental research carried out within the project will enable European industrial stakeholders to develop more energy efficient ICT devices (such as low power magnetic logic and storage devices) and more sensitive diagnostic tools for bio-sensing and manipulation of individual biomolecules (such as PMA DW sensors), increasing the competitiveness of the European industry in the global market. 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.

5 Website address and contact details

The project public website is accessible at:

https://www.ptb.de/emrp/spincal.html

JRP-Coordinator contact details:

Hans Werner Schumacher,

Phone: +49 531 592 2500

E-mail: hans.w.schumacher@ptb.de

6 List of publications

1. N. Liebing, S. Serrano-Guisan, P. Krzysteczko, K. Rott, G. Reiss, J. Langer, B. Ocker and H.W. Schumacher: *Tunneling magneto thermocurrent in CoFeB/MgO/CoFeB based magnetic tunnel junctions,* Applied Physics Letters **102,** 242413 (2013)
2. A. Ben Hamida, S. Sievers, K. Pierz and H. W. Schumacher: *Broadband ferromagnetic resonance characterisation of GaMnAs thin films,* Journal of Applied Physics **114,** 123704 (2013)
3. X.K. Hu, P. Krzysteczko, N. Liebing, S. Serrano-Guisan, K. Rott, G. Reiss, J. Kimling, T. Böhnert, K. Nielsch, H.W. Schumacher: *Magneto-thermoelectric figure of merit of Co/Cu multilayers,* Applied Physics Letters **104,** 092411 (2014)
4. A. Caprile, M. Pasquale, M. Kuepferling, M. Coïsson, T. Y. Lee, S. H. Lim: *Microwave properties and damping in [Pt/Co] multilayers with perpendicular anisotropy,* IEEE Magnetic Letters **5,** 3000304 (2014)
5. C. Heiliger, M. Czerner, N. Liebing, S. Serrano-Guisan, K. Rott, G. Reiss, Hans W. Schumacher: *Unusual angular dependence of tunneling magneto-Seebeck effect,* http://arxiv.org/abs/1311.2750 (2013)
6. H. Corte-León, A. Beguivin, P. Krzysteczko, H. W. Schumacher, A. Manzin, R. P. Cowburn, V. Antonov and O. Kazakova: *Influence of geometry on domain wall dynamics in permalloy nanodevices,* IEEE Transactions on Magnetics **51,** 4001304 (2015)
7. H. Corte-León, P. Krzysteczko, H. W. Schumacher, A. Manzin, V. Antonov and O. Kazakova: *Tailoring of domain wall devices for sensing applications,* IEEE Transactions on Magnetics **50,** 7101004 (2014)
8. H. Corte-León, V. Nabaei, A. Manzin, J. Fletcher, P. Krzysteczko, H. W. Schumacher and O. Kazakova: *Anisotropic Magnetoresistance State Space of Permalloy Nanowires with Domain Wall Pinning Geometry,* Scientific Reports **4,** 6045 (2014)
9. N. Tesarová, D. Butkovicova, R. P. Campion, A. W. Rushforth, K. W. Edmonds, P. Wadley, B. L. Gallagher, E. Schmoranzerová, F. Trojanek, P. Maly, P. Motloch, V. Novak, T. Jungwirth, and P. Nemec: *Comparison of micromagnetic parameters of the ferromagnetic semiconductors (Ga,Mn)(As,P) and (Ga,Mn)As,* Physical Review B **90,** 155203 (2014)
10. A. J. Ramsay, P. E. Roy, J. A. Haigh, R. M. Otxoa, A. C. Irvine, T. Janda, R. P. Campion, B. L. Gallagher, J. Wunderlich: *Optical spin transfer torque driven domain wall motion in ferromagnetic semiconductor,* Physical Review Letters **114,** 067202 (2015)
11. D. Meier, D. Reinhardt, M. van Straaten, C. Klewe, M. Althammer, M. Schreier, S. T. B. Goennenwein, A. Gupta, M. Schmid, C. H. Back, J-M. Schmalhorst, T. Kuschel, G. Reiss: *Longitudinal spin Seebeck effect contribution in transverse spin Seebeck effect experiments in Pt/YIG and Pt/NFO,* Nature Communications **6,** 8211 (2015)
12. A. Sola, M. Kuepferling, V. Basso, M. Pasquale, T. Kikkawa, K. Uchida and E. Saitoh*: Evaluation of thermal gradients in longitudinal spin Seebeck effect measurements,* Journal of Applied Physics **117,** 17C510 (2015)
13. M. Kuepferling, S. Zullino, A. Sola, G. Durin, M. Pasquale, G. Bertotti, B. Van de Wiele, K. Rott, G. Reiss: *Vortex Dynamics in Co-Fe-B Magnetic Tunnel Junctions in Presence of Defects,* Journal of Applied Physics **117**, 17E107 (2015)
14. A. Manzin, E. Simonetto, G. Amato, V. Panchal, and O. Kazakova: *Modeling of graphene Hall effect sensors for microbead detection,* Journal of Applied Physics **117,** 17B732 (2015)
15. H. Corte-León, P. Krzysteczko, H. W. Schumacher, A. Manzin, D. Cox, V. Antonov, and O. Kazakova: *Magnetic nanoparticle detection using domain wall-based nanosensor,* Journal of Applied Physics **117,** 17E313 (2015)
16. T. Wren and O. Kazakova: *Anisotropic Magnetoresistance Effect in Sub-Micron Nickel Disks,* Journal of Applied Physics **117,** 17E134 (2015)
17. T. Wren, B. Gribkov, V. Petrashov, and O. Kazakova: *Phase Diagram of Magnetic States in Nickel Submicron disks,* Journal of Applied Physics **118,** 023906 (2015)
18. J. Wells, J. H. Lee, R. Mansell, R. Cowburn, and O. Kazakova: *Controlled Manipulation of Domain Walls in Ultra-Thin CoFeB Nanodevices,* Journal of Magnetism and Magnetic Materials **400,** 15 (2016)

19. H. Corte-León, B. Gribkov, P. Krzysteczko, F. Marchi, J.-F. Motte, H. W. Schumacher, V. Antonov, N. M. Dempsey, and O. Kazakova: *Magnetic scanning gate microscopy of a domain wall nanosensor using microparticle probe,* Journal of Magnetism and Magnetic Materials **400,** 15 (2016)
20. V. Basso, E. Ferraro, A. Sola, A. Magni, M. Kuepferling, M. Pasquale: *Non-equilibrium thermodynamics of the longitudinal spin Seebeck effect,* Physics Procedia **75,** 939-947 (2015)
21. Patryk Krzysteczko, Xiukun Hu, Niklas Liebing, Sibylle Sievers, and Hans W. Schumacher: *Domain wall magneto-Seebeck effect,* Physical Review B: Rapid Communications **92,** 140405(R) (2015)
22. H. Corte-León, P. Krzysteczko, F. Marchi, J-F. Motte, A. Manzin, H. W. Schumacher, V. Antonov, and O. Kazakova: *Detection of a magnetic bead by hybrid nanodevices using scanning gate microscopy,* AIP Advances **6,** 056502 (2016)
23. J. Wells, P. Krzysteczko, A. Caprile, B. Gribkov, H.W. Schumacher, J.H. Lee, R. Cowburn, O. Kazakova: *Magnetic particle nanosensing by nucleation of domain walls in ultra-thin CoFeB/Pt devices,* IEEE Transactions on Magnetics **52,** 4001705 (2016)
24. V. Basso, E. Ferraro, A. Magni, A. Sola, M. Kuepferling and M. Pasquale: *Nonequilibrium thermodynamics of the spin Seebeck and spin Peltier effects,* Physical Review B **93,** 184421 (2016)
25. A. Caprile, A. Manzin, M. Coisson, M. Pasquale, H. W. Schumacher, N. Liebing, S. Sievers, R. Ferreira, S. Serrano-Guisan and E. Paz: *Static and dynamic analysis of magnetic tunnel junctions with wedged MgO barrier,* IEEE Transactions on Magnetics **51,** 4400304 (2015)
26. T. Vemulkar, R. Mansell, A. Fernández-Pacheco and R. P. Cowburn: *Toward flexible Spintronics: perpendicularly magnetised synthetic antiferromagnetic thin films and nanowires on polyimide substrates,* Advanced Functional Materials **26,** 4704-4711 (2016)
27. R. Mansell, A. Beguivin, D. C. M. C. Petit, A. Fernández-Pacheco, J. H. Lee and R. P. Cowburn: *Controlling nucleation in perpendicularly magnetised nanowires through in-plane shape,* Applied Physics Letters **107,** 092405 (2015)
28. Dorothée Petit, Peter R. Seem, Marine Tillette, Rhodri Mansell and Russell P. Cowburn: *Two-dimensional control of field-driven magnetic bubble movement using Dzyaloshinskii–Moriya interactions,* Applied Physics Letters **106,** 022402 (2015)
29. X. K. Hu, H. Dey, N. Liebing, H. W. Schumacher, G. Csaba, A. Orlov, G. H. Bernstein and W. Porod: *Coherent precession in arrays of dipolar-coupled soft magnetic nanodots,* Journal of Applied Physics **117,** 243905 (2015)
30. X.K. Hu, H. Dey, N. Liebing, G. Csaba, A. Orlov, G.H. Bernstein, W. Porod, P. Krzysteczko, S. Sievers and H.W. Schumacher: *Edge-Mode Resonance-Assisted Switching of Nanomagnet Logic Elements,* IEEE Transactions on Magnetics **51,** 3401004 (2015)
31. L. Nádvorník, P. Němec, T. Janda, K. Olejník, V. Novák, V. Skoromets, H. Němec, P. Kužel, F. Trojánek, T. Jungwirth & J. Wunderlich: *Long-range and high-speed electronic spin-transport at a GaAs/AlGaAs semiconductor interface,* Scientific Reports **6,** 22901 (2016)
32. Hu, X.K. et al: Magnetothermoelectric figure of merit of Co/Cu multilayers, Appl Phys Letters 104 (2014)

Submitted:

33. Tom Wren, Boris Gribkov, Sergey Vdovichev, Olga Kazakova: *The consequence of magnetic probe choice in magnetic force microscopy*
34. J. Wells, A. Fernandez-Scarioni, H. W. Schumacher, D. Cox, R. Mansell, R. Cowburn, O. Kazakova: *Detection of individual iron-oxide nanoparticles with vertical and lateral sensitivity using domain wall nucleation in CoFeB/Pt*
35. P. Krzysteczko, J. Wells, A. Fernandez-Scarioni, Z. Soban, T. Janda, X, Hu, V. Saidl, R. P. Campion, R. Mansell, J.-H. Lee, R. Cowburn, P. Nemec, J. Wunderlich, O. Kazakova, and H. W. Schumacher*: Nanoscale thermo-electrical detection of magnetic domain wall propagation*

i FP7: ICT – Information and Communication Technologies: Updated Work Programme 2011 and Work Programme 2012.

ii ITRS Roadmap 2011, Emerging Research Materials (EMR). http://www.itrs.net/.