European Partnership on Metrology
Call 2023 –Fundamental Metrology, Industry, Normative and Research Potential

Selected Research Topic number: **SRT-f12**
Version: 1.0

Title: Quantitative measurements of the spin Hall angle in modern spintronic devices

Abstract

Research in spintronics focuses on improving device and energy efficiency by exploiting novel concepts, such as the spin-orbit-torque (SOT) and efficient spin-charge interconversion. Spintronics is the key to novel types of applications, such as quantum, probabilistic and neuromorphic computing, energy harvesting and spin based thermoelectric generators, microwave and THz emitters, SOT based sensors and spin-based energy storage. The performance and energy efficiency of spintronic devices depends on an efficient spin-charge interconversion, based on the spin Hall effect and quantified by the spin Hall angle. Proposers should focus on the development of reliable techniques for quantifying the spin-charge interconversion. The determination of the performance and energy efficiency of the spintronic devices should be explored mainly for artificial intelligence and machine learning.

Keywords

spintronics, spin Hall effect, spin Hall angle, spin-charge interconversion, spin-orbit torques, spin accumulation, spin diffusion length, machine learning, micromagnetics

Background to the Metrological Challenges

One of the main mechanisms for spin-charge interconversion is the spin Hall effect (SHE). It occurs typically through the interface between a magnetic (ferro-, ferri-, antiferro-magnetic) thin film and a "non-magnetic" thin film (e.g. heavy metal), and is quantified by the spin Hall angle (SHA). Different SHA measurement techniques show large discrepancies. These discrepancies depend on material parameters, film thickness variations, film inhomogeneities, defects and interface quality. Techniques of "high-throughput" character (e.g. THz emission spectroscopy, VNA-FMR, etc.) are preferable, in order to create a sufficient measurement statistic as input for an advanced data analysis, and to explore methods potentially suited for industrial inline production quality control. These techniques should be characterised by an automatised, high-speed acquisition and reduced sample preparation steps (e.g. patterning). Theoretical models of spin-charge interconversion include intrinsic material parameters, interface properties, defects and inhomogeneities, different mechanisms of spin scattering and measurement conditions, like temperature. Different measurement techniques may have different sensitivity to these parameters influencing the measured values. Machine learning (ML) provides tools, such as a principal component and parameter sensitivity analysis, able to extract the main components, and to analyse complex problems without the need of a model, but on the basis of large trainings sets with known parameters. Micromagnetic simulations ideally complement the ML approach by offering an established method for the creation of a well-defined training set. The variety of parameters influencing spintronic devices leads to an apparent statistical distribution of the spin Hall angle without a simple way to identify and quantify them. In order to be able to validate theoretical models or machine learning models with black box character, a complete characterisation of the parameters potentially influencing the measurement result and its uncertainty is required. An advanced characterisation of spintronic devices includes 1) an accurate determination of the global parameters, such as saturation magnetisation (M_s), anisotropy, conductance, film thickness and interface roughness; 2) exploiting scanning probe techniques (spin-SEM, SThM, SMM, MFM etc.) for a local measurement of conductivity, temperature, magnetic parameters, etc. in order to determine the influence of inhomogeneities; 3) developing highly sensitive and/or resolved methods (e.g. NV based quantum sensing) for the determination of spin accumulation or spin diffusion length. The spin-charge interconversion is a critical point to make low-power spintronics compatible with charge-based technologies. The (inverse) SHE is currently the most feasible way for spin-charge interconversion, but an assessment of the reliability of quantitative measurements of the SHA and its relation to performance and energy efficiency are still missing.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the traceable measurement and characterisation of the spin Hall angle in modern spintronic devices.

The specific objectives are

1. To perform quantitative measurements of the spin Hall angle and investigate their reproducibility. To determine the current level of accuracy and reproducibility of the measurement of spin-charge interconversion. To apply different experimental set-ups and protocols, while considering the material parameters, film thickness variations, film inhomogeneities, defects and interface quality. Techniques of "high-throughput" character (THz emission spectroscopy, VNA-FMR, etc.) should be considered, in order to produce a sufficient measurement statistic as input for an advanced data analysis. To explore methods potentially suitable for industrial inline production quality control.
2. To develop and apply theoretical models (analytical and numerical), combined with statistical data processing and machine learning, in order to analyse the origin of data spread and uncertainties of spin Hall angle measurements. To determine the relevant parameters and investigate ways of improving the related uncertainties and reproducibility. To determine the performance and energy efficiency of spintronic devices.
3. To characterise spintronic devices by developing and applying sensitive and/or resolved techniques. This characterisation will include (i) investigating the global parameters (saturation magnetisation (Ms), anisotropy, conductance, film thickness and interface roughness), (ii) determining the influence of inhomogeneities and performing local measurement of conductivity, temperature, magnetic parameters with different scanning probe techniques (spin-SEM, SThM, SMM, MFM etc.), and (iii) developing highly sensitive and/or resolved methods (e.g. NV based quantum sensing) for the determination of spin accumulation or spin diffusion length. Based on these results, to validate and further improve the theoretical models of Objective 2.
4. To facilitate the take up of the technology and measurement infrastructure of the spin Hall angle developed in the project by the measurement supply chain (NMIs, spintronics research organisations, standards developing organisations) and end users (spintronic devices manufacturers, semiconductor industry, electrical engineering industry). To support the European and International stakeholders by publishing and disseminating open access good practice guides (e.g. on the developed measurement techniques (Objective 1), the spin-charge interconversion modelling (Objective 2), and the spintronic devices characterisation (Objective 3)).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, including other European Partnerships, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.0 M€ and has defined an upper limit of 2.5 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 40 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the spintronics research sector.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of the Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Time-scale

The project should be of up to 3 years duration.