

Title: Quantum anomalous Hall effect materials and devices for metrology

Abstract

Graphene-based quantum Hall resistor devices have been earmarked as a possible application for the primary resistance standards. In addition, topological insulators have given access to time-reversal symmetry-protected spin-orbit coupling, which, when broken by magnetic order, leads to the Quantum Anomalous Hall effect (QAHE). The prospect of realising the QAHE at high temperatures and zero magnetic field makes it a candidate for the next generation of primary resistance standards. This will impact the scientific community by including a spectroscopic understanding of topological insulators and the European metrology community by realising a future 'quantum electrical metrology toolbox' setup that will benefit applications in spintronics, low-power consumption electronics and topological quantum computing.

Keywords

Quantum Hall resistance standard, topological insulators, quantum anomalous Hall effect, spintronics, scanning microwave microscopy, magnetic force microscopy, low power electronics, quantum computing

Background to the Metrological Challenges

Electrical metrology is at the epicentre of practically all measurements, electric or non-electric (such as mass, via the Kibble balance, and temperature based on the Boltzmann constant) and is at a critical juncture concerning the evolution of primary resistance standards (PRS). Electrical metrology requires that the electrical units are realised at unsurpassed accuracy levels. The quantum Hall effect (QHE) with parts-per-billion (ppb) resistance quantisation accuracy presently represents the "gold standard" of PRS in electrical metrology. However, the QHE devices based on established material systems must be operated under challenging environmental conditions involving complex and expensive cryogenic apparatus including superconducting solenoids, making its universal adoption beyond NMIs challenging. The discovery of exotic materials and physics has led to a new kind of Hall effect and a class of materials offering a path to circumvent the necessity to form Landau levels and control carrier mobilities for use as PRS with unsurpassed accuracy in 'relaxed conditions': the so-called quantum anomalous Hall effect (QAHE) in topological insulators, which enables realising the QHE at zero external magnetic fields.

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 Quantum Anomalous Hall effect (QAHE) materials and devices and primary resistance standards. The specific objectives are:

1. To improve the growth of magnetically doped topological insulator (TI), (e.g., Bi_2Te_3 and Sb_2Te_3) thin film samples by molecular beam epitaxy on closely lattice matched substrates. To explore the effects of anisotropic magnetic insulator layers interfaced with TIs and produce high structural quality materials with properties optimised for the QAHE.
2. To investigate the electronic, structural, magnetic, and magneto-electronic properties of the above samples by using QAHE devices under various temperatures, currents, and applied magnetic field for different growth conditions. To investigate the limitations of QAHE, i.e., low critical temperatures and currents when working on precision growth-control of interfaces.

3. To investigate fabricated samples by scanning probes and magnetometry techniques at low temperatures, and to characterise the magnetic and structural properties with high lateral resolution.
4. To develop and carry out a detailed metrological assessment of optimised QAHE devices, both at sub-Kelvin and above 1 K temperatures, aiming at QAHE resistance quantisation accuracy between 1 and 10 ppm, above 1 K, at currents above 1 μ A and at low-to-zero applied magnetic field.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by standards developing organisations (BIPM), end users interested in applications, such as spintronics and topological quantum computing and advance the research and progress in the field of TIs.

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. In particular, proposers should outline the achievements of the EMRP SIB51 GraphOhm and EMPIR 20FUN03 COMET and how their proposal will build on those.

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 electronics 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.