Title: The quantum anomalous Hall effect in topological insulators

Abstract

Electrical quantum effects are at the heart of the new SI: electrical units, the kilogram, and the realisation of the kelvin use them to link to the roots of the new SI, the fundamental constants. However, their widespread use is limited by challenging operating requirements of low temperature and high magnetic field. A promising new material class, topological insulators (TI), has emerged which allows the quantum Hall resistors (QHR) to be realised without a magnetic field and has the potential to work at less challenging temperatures. The effect is called the quantum anomalous Hall effect (QAHE). Research effort is required to progress this technology towards a future quantum resistance standard which could operate "on the workshop floor".

Keywords

Quantum resistance standards, topological insulators, magnetotransport, spintronics

Background to the Metrological Challenges

Quantum standards of electrical units (based on the quantum Hall effect for resistance and the Josephson effect for voltage) are important not only for electrical measurements but in the future realisations of the unit of mass and temperature will be dependent on these quantum electric effects as well. However their use is limited to metrology institutes due to the challenging nature of the operating conditions such as low temperatures and high magnetic fields. Graphene has been studied as a potential material for novel QHR devices as it works under relaxed temperature conditions but it still needs a magnetic field for resistance quantisation. A promising new material class, known as topological insulators (TI), has emerged which allows the QHR to be realised without a magnetic field. Only a small number of organisations are able to fabricate the material necessary for the realisation of such novel QHR devices and a more coordinated research effort is required to progress this technology.

For presently available TI devices, measurements of the resistivity tensor require very low bias currents in the nanoampere range. This sets high demands on the experimental techniques. For future metrological applications of QAHE devices, their resistance quantisation has to be demonstrated in (magneto)transport experiments at an accuracy level at least three orders of magnitude better than has been shown to date.

The key advantage of the QAHE state is that it is topologically robust, and by definition impervious to perturbations. As long as the band structure of the material is not fundamentally changed by defects or impurities, these factors have no influence at all. The materials are so new that a detailed optimisation of the material properties is still in progress. Questions such as the impact of crystal quality, domain twining, homogeneity of the distribution of magnetic dopants on the sample quality still need to be explored.

Elevation of the operation temperature for quantum Hall resistors based on the QAHE is a key requirement. So far, the QAHE has been demonstrated experimentally at maximum temperatures of around one kelvin; this limit was set by material imperfections (doping and magnetic properties). According to the current understanding of the QAHE in TI systems there is no fundamental temperature limit, but only limits imposed by the materials used in the implementation. A better understanding of the TI material properties, especially the magnetic ones, is therefore needed.

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 (magneto)transport, magnetic and structural properties of topological insulator (TI) systems.

The specific objectives are:

1. To develop techniques to improve the growth of magnetically (vanadium) doped topological insulator film samples of the $(Bi_xSb_{2-x})Te_3$ family on appropriate substrates and using these techniques to produce samples of increased crystal quality with properties optimised for the quantised anomalous Hall effect.
2. To accurately characterise the electronic transport properties of the samples under variations of temperature and applied magnetic field – in particular by precision measurements of the resistivity tensor in dependence of these variations with a target uncertainty of at least 0.1 ppm and by studying of electronic transport noise.
3. To accurately characterise the magnetic and structural properties of the samples with high lateral resolution using scanning probe techniques such as SQUID magnetometry or magnetic force microscopy at low temperatures.
4. To evaluate the characterisation and growth results, through interaction with theoretical physics groups, to achieve a better understanding of the nature of the ferromagnetic state in topological insulator (TI) systems and the related magnetotransport properties.
5. To disseminate the results among academic and metrology communities in Europe and worldwide, in order to advance the research and progress in the emerging field of TIs, as well as in the wider stakeholder groups interested in applications (e.g. spintronics, quantum manipulation and computing, and low-power consumption electronics).

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, 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 project SIB51 and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.5 M€, and has defined an upper limit of 1.8 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 40 % of the total EU Contribution to the project.

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,

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 EMPIR 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.