Title: Quantum impedance metrology based on graphene

Abstract

Recent developments utilising the quantum Hall effect (QHE) in graphene can potentially lead to robust, simple-to-operate and economically practical realisations of electrical impedance units (ohm, farad, henry) in the new SI. These will require primary AC quantum impedance standards based on graphene (preferably cryogen-free and compact) and automated impedance bridges.

Keywords

Graphene, quantum Hall effect, impedance, resistance, capacitance, quantum impedance standard, quantum resistance standard, new SI.

Background to the Metrological Challenges

Development of graphene-based primary resistance standards has been one of the big success stories of European metrology research in recent years. The European state-of-the-art in this field is currently the leading state-of-the-art in the world. Quantised Hall Resistance (QHR) in an epitaxial graphene device on SiC substrate has already shown to be equal to QHR in a GaAs device at relative uncertainty below 10^{-10}. Recent preliminary results have indicated the great potential of chemical vapour deposited (CVD) graphene on SiC substrate where the flatness of the QHR plateau has been demonstrated at 10^{-9}-level relative uncertainty down to magnetic field of 3.5 T. However, fabrication technology for graphene devices is still not mature, and the previously mentioned results have been obtained in individually selected samples. Considerable further work is still needed especially in optimising graphene devices for robust, low-field/high-temperature/high-current operation and particularly for AC applications.

Results from the first AC experiments on QHE in graphene, were published in 2014. They indicated the great potential of graphene in AC metrology, since the quantum Hall plateaus measured with AC were found to be flat within one part in 10^7; much better than for plain GaAs quantum Hall devices.

The target is an impedance standard for a wide range of resistance, capacitance, and inductance values, that uses the QHE in graphene as an intrinsic "fixed point" reference. Design and construction of such a device is a special challenge. The accuracy of the device should be improved considerably compared to present state of the art in the case where pure capacitance or inductance is compared with quantum resistance.

Use of cryogen-free refrigerators for reaching temperatures of about 4 K and below have recently increased considerably due to development of refrigeration techniques, partly driven by the increasing price of liquid helium. In addition, cryogen-free setups have several benefits compared to their liquid-helium-cooled counterparts, including: ease of use and freedom of designing the geometry and dimensions of the system. So far, metrology-level quantum Hall experiments in graphene have been performed in conventional liquid-helium-cooled cryostats. The applicability of cryocooler based systems at AC frequencies needs to be explored, since system-inherent microphonic effects, in combination with magnetic fields, are expected to compromise precision measurements.

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 impedance devices based on graphene.

The specific objectives are

1. To advance the development of graphene QHE devices beyond the current state of the art in order to obtain graphene devices with very homogeneous low charge carrier densities optimised for both AC and DC applications. The quantitative objective is to develop graphene devices with QHE plateaus with relative accuracy better than 10^{-9} at B < 2 T at DC and 10^{-8} at AC in a simple-to-operate low-temperature system with base temperature between about 3 K and 5 K.
2. To develop primary AC quantum impedance standards based on graphene and automated impedance bridges for the capacitance range from 10 pF to 10 nF at frequencies up to 100 kHz.
3. To improve considerably the user-friendliness of both primary DC resistance and AC impedance metrology by developing a cryogen-free quantum calibration system based on QHE in graphene.
4. To explore future possibilities of graphene-based electrical metrology, including an experimental feasibility study on operating a graphene quantum Hall device and Josephson array voltage standards in the same cryogen-free cryostat, and demonstration of quantised Hall resistance in an array of graphene Hall bars.
5. To support calibration laboratories, industrial companies and measurement equipment producers with a shorter primary traceability chain for resistance/impedance standards and measurement devices.

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources outside Europe is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry.

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 GraphOhm and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.8 M€, and has defined an upper limit of 2.1 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 21 % of the total EU Contribution to the project. Any deviation from this must be justified.

Any industrial partners that will receive significant benefit from the results of the proposed project are expected to be unfunded 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,
- Transfer knowledge to the electrical measurement 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 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.