Publishable Summary for 18SIB07 GIQS
Graphene impedance quantum standard

Overview

The aim of this project is to enable an economically efficient traceability of impedance quantities to the defining constants of the revised International System of Units (SI). This will simplify the calibration support which European and other National Metrology Institutes (NMIs) provide to the electronics industries. New and easier to operate measurement bridges, convenient and easier to use graphene quantum standards, and methods to combine them will be developed. Cryogenic system components for operating the quantum devices will be developed for the challenging requirements of impedance measurements.

Need

Electronic components rely, for their international competitiveness, on the application of mutually agreed measurements during their production and use. Electrical impedance (capacitance, inductance) is a quantity in this field that is practically of equal importance to voltage and resistance. It is more important than current, as the sensors, which are used in numerous contexts either rely on resistance or, more often, on contactless capacitive methods. For voltage and resistance, the “gold standards” of traceability, namely the Josephson effect (JE) and the quantum Hall effect (QHE), have been used in major NMIs for a long time. Impedance standards on the other hand still require many calibration steps with complicated measurement setups to trace them to the QHE.

At present, only a very few quantum standards are in use outside of the NMIs due to the high investment, high operational costs, and complexity of use. The quantum traceability of the impedance unit, the farad, would clearly benefit if an economically viable route was established. However, the complex calibration chains from the QHE to different capacitance and inductance values only exist in some of the largest NMIs. This is not acceptable and a shorter and simpler traceability chain of impedance to quantum standards, which is available and affordable for all NMIs, calibration centres and industries (e.g. automotive and mobile electronics), is clearly needed.

At this point, the need to utilise graphene comes into play: its potential for metrology was understood almost immediately, because in graphene the QHE can exist at much lower magnetic fields (below 6 T) and at higher temperatures (above 4 K) than in conventional systems. The fundamental constant realisation for the DC QHE has been simplified by using graphene. The realisation of the corresponding fundamental constant for the AC units of impedance, i.e. capacitance and inductance, will also benefit from graphene with its much less demanding operational margins with respect to temperature and magnetic field. In addition, simpler and more flexible AC instrumentation need to be further developed, optimised and adapted for the use of graphene devices that are directly operated in the AC regime, thus avoiding a troublesome DC resistance to AC impedance transfer procedure.

Objectives

The overall objective is to combine novel digital impedance measurement bridges with the QHE material graphene in a simplified cryogenic environment. This will provide European NMIs, calibration centres and industry with the technology that is needed to enable the practical realisation of electrical impedance units (ohm, farad, henry) in the revised SI.

The specific objectives of the project are:

1. To optimise and to tailor graphene material and graphene devices in order to improve the understanding of the graphene AC quantised Hall effect (AC-QHE), as the basis for the traceability of impedance units to the QHE at temperatures of 4 K or higher in magnetic fields that are as low as possible - at most 6 T.

2. To advance digital bridges for the capacitance range from 10 pF to 10 nF at frequencies up to 100 kHz, and to develop an impedance bridge working with spectrally pure Josephson voltages up to 50 kHz in the entire complex plane.
3. To combine graphene devices with a Josephson impedance bridge (with a target uncertainty below 0.01 µΩ/Ω), and with a full digital bridge for simplified operation, (with a target uncertainty in the 0.1 µΩ/Ω range), in order to provide traceability for capacitance to the QHE.
4. To develop and investigate a cryo-cooler system hosting the superconducting Josephson device and the graphene device, both operating at AC and serving as the core element of a quantum resistance and impedance standard in the revised SI.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (e.g. graphene manufacturers), standards developing organisations and end users (e.g. NMIs and calibration centres as well as the European Commission's Graphene Flagship).

Progress beyond the state of the art

Fabrication of graphene-based impedance quantum standards: The potential of graphene devices for use as impedance standards has not yet been validated as they need optimisation with regards to the special AC conditions which go beyond the goals of EMRP JRP SIB51 GraphOhm. Within this project, the consortium will develop graphene devices which are stable in the long-term and which are optimised for AC applications for use in impedance metrology with an accuracy of 10^{-8}.

Advanced digital bridges: Classical transformer-based bridges for impedance calibration are limited in their frequency range, difficulty and they are lengthy to handle. The partners will develop programmable, reconfigurable bridges that are usable over a large frequency range and which go beyond the goals of the EMRP JRP SIB53 AIMQuTE. Within the project digital bridges will be developed for the capacitance range from 10 pF to 10 nF at frequencies up to 100 kHz, and an impedance bridge will be developed working with spectrally pure Josephson voltages up to 50 kHz in the entire complex plane.

Traceability of the capacitance unit: The combination of Josephson full digital impedance bridges for the realisation of a graphene-based quantum impedance standard was not attempted before. In this project for the first time a prototype of an impedance quantum standard based on graphene is planned with a digital impedance bridge and a state of the art dual Josephson impedance bridge with a target accuracy of 10^{-8}.

Cryo-cooler system for graphene-based impedance measurements: Josephson voltage standard devices are typically very sensitive to external magnetic fields, whereas magnetic fields are indispensable for QHE devices. Therefore, the combination of both elements in one cryostat is not yet available. In this project, an experimental feasibility study on the operation of a graphene quantum Hall device and Josephson voltage standards in the same cryogen-free cryostat will be carried out.

Results

To optimise and to tailor graphene material and graphene devices in order to improve the understanding of the graphene AC quantised Hall effect (AC-QHE), as the basis for the traceability of impedance units to the QHE at temperatures of 4 K or higher in magnetic fields that are as low as possible - at most 6 T.

Fabrication of epitaxial graphene was carried out and optimised in three partner institutes. The resulting graphene layers are of high quality and they consist of homogenous monolayer graphene over areas large enough for the fabrication of quantum Hall devices up to the mm range. [1] A molecular post-growth doping techniques was applied in order to reduce the electron density to values below 10^{11} cm^{-2} which allows us to choose a working point at low magnetic fields of $B < 6$ T. Optimisation of the fabrication process of quantum Hall devices was started. New metal contacts were tested which have resulted in mechanically stable ohmic contacts with low resistance values of a few milliohm. [1] The quality of the fabricated quantum Hall devices was tested in a first step by dc-quantum Hall measurements. With these experiments an accuracy of 3×10^{-9} could be reached at $B = 5$ T for reproducing the nominal resistance value in the quantum Hall plateau of $h/2e^2$.

To advance digital bridges for the capacitance range from 10 pF to 10 nF at frequencies up to 100 kHz, and to develop an impedance bridge working with spectrally pure Josephson voltages up to 50 kHz in the entire complex plane.

Digitally-assisted bridges were fabricated in the partners' labs. This was realised by assembling new bridges and by improving existing ones, respectively. The function of the new setups were successfully tested. One of the digitally-assisted bridges was evaluated at capacitances of 10 pF to 10 nF at constant standard frequencies of 1 kHz and 1.541 kHz. For a 10-nF-standard capacitor an accuracy of 10^{-8} in the frequency range from 1 kHz - 20 kHz was measured. A fully digital bridge in a four-terminal pair configuration was realised and successfully tested in the low frequency range up to 5 kHz.

To combine graphene devices with a Josephson impedance bridge (with a target uncertainty below 0.01 µΩ/Ω), and with a full digital bridge for simplified operation, (with a target uncertainty in the 0.1 µΩ/Ω range), in order to provide traceability for capacitance to the QHE.

Circuit models for the ac-quantum Hall effect were developed and tested. The simulation calculations allow the estimation and prediction of stray parameters of the quantum Hall devices in ac operation. For the low-temperature experiments in the magnet cryostats new cryo-probes were developed and manufactured that are specially adapted to ac applications. A first cryo-system in one partner lab was finished and preliminary dc experiments have proven the metrological functionality of the cryo-system including the new cryo-probe.

To develop and investigate a cryo-cooler system hosting the superconducting Josephson device and the graphene device, both operating at AC and serving as the core element of a quantum resistance and impedance standard in the revised SI.

Two different approaches were designed for the cryo-cooler system hosting the Josephson and the graphene device and the set-up has started in two partner laboratories. First tests of one cryostat were already carried out at base temperature and no additional noise was found in quantum Hall resistance measurements.

Impact

To promote the uptake of the progress in the field of impedance metrology and epitaxial graphene fabrication technology generated in this project, as well as to share insights generated throughout the project, results were shared broadly with scientific and metrology end-users. One paper was published in the international journal Applied Physics Letters (listed in the next section). 9 presentations were made at conferences, including the Graphene Flagship's Graphene Week held in Helsinki, Finland, September 2019. An overview of the project's goals and activities was given at the 2019 contact person meeting of the EURAMET committee TC-EM (Electricity and Magnetism). Two presentations were shown in university seminars focussed on high school students. Lab training was completed for a scientist from a partner institute. A newsletter which summarises goals and the first results of the project was produced and distributed to stakeholders. To inform stakeholders, interested end users and the scientific community two online platforms were created, the project's homepage and a GIQS LinkedIn group which also provides the opportunity for an exchange of ideas and discussions. Moreover, a survey was launched to improve feedback from stakeholders.

Impact on industrial and other user communities

This project will establish a new primary standard of impedance. At present, industrial and other user communities rely on a long chain of calibrations, originating at the BIPM or few large NMIs, and extending over smaller NMIs, and/or commercial calibration service providers to eventually reach the end user. This lengthy chain will be shortened with a simpler, cheaper and easier to operate primary standard. The impact on industrial and other end users will gain its full thrust after an initial post-project phase when the knowledge and know-how created in this project has been taken up by instrumentation companies and converted into marketable solutions e.g. a digital impedance bridge based on conventional electronics. The early impact will be on industrial instrumentation manufacturers and large-scale calibration service providers, which will be able to use the enhanced calibration quality enabled by the new primary impedance quantum standard to provide scientifically sound services with improved performance, reliability and cost efficiency.

Impact on the metrology and scientific communities

At present many small NMIs obtain traceability for their national resistance and capacitance standards from other NMIs or from BIPM due to the high acquisition and operational costs of primary quantum Hall systems. For example, from 2013 – 2017, BIPM issued 159 certificates for resistance and 127 for capacitance for 36 NMIs. Eighteen of them were from Europe. Therefore, at the NMI level, one of the major impacts of the project will be to provide a direct and user-friendly realisation of impedance units in the “revised SI” at the “point of calibration”, thereby relaxing the NMIs’ dependence on BIPM, and releasing BIPM’s resources for more important research tasks.

To create early impact in the scientific communities, research papers will be submitted for publication in high impact peer-reviewed journals. Dissemination workshops will also be organised for different target groups.

As explained in the draft mise en pratique for the ampere and other electrical units in the revised SI, the unit farad can be realised by comparing the quantised Hall resistance to the impedance of the unknown capacitance using, for example, a quadrature bridge. Development of digital solutions, e.g. digital conventional bridges, for such a primary unit realisation will be one of the main impacts of this project. The graphene-based quantum Hall resistance (QHR) device will also be valuable in the realisation of other electrical units of the revised SI, such as the unit ampere that can be realised *“by using Ohm’s law, the unit relation A = V/Ω, and using practical realisations of the SI derived units volt V and ohm Ω, based on the Josephson and quantum Hall effects, respectively”*. For those NMIs who decide to implement the new impedance quantum standard, such direct access to the primary capacitance realisation will enable them to claim improved CMCs in this field.

Impact on relevant standards

This project will create impact as an impedance calibration system based on a quantum standard will become available. How this new primary quantum standard, and especially its possible use outside of authorised NMIs, will impact the international measurement system and written standards need to be discussed by the relevant bodies of the international measurement system. However, this project will actively contribute to key European and international committees (e.g. Consultative Committee for Electricity and Magnetism (CCEM)) to spread the required information and knowledge.

In this context, the most important regulatory document is EN ISO/IEC 17025, “General requirements for the competence of testing and calibration laboratories”, which defines in general terms the technical requirements for good practice calibrations in section 6.5 (2017). Furthermore, calibration is an important and recurring subject in the EC directive MID 2004/22/IEC on measuring instruments. National laws and directives in the EU member states concerning the units of measurements and how they are to be implemented are relevant law whose simpler, better, and more cost-effective compliance will be targeted by the developments in this project.

Longer-term economic, social and environmental impacts

Achieving the objectives of this project will respond to the need for a shorter traceability chain to quantum impedance standards by using the huge metrological potential of graphene. It will also preserve and strengthen Europe’s lead in the metrological applications of the QHE in graphene and in digital impedance metrology.

The European calibration services market is estimated to be worth $1.55 billion in 2018, with more than 40 % of the total being for electrical calibrations, which include instrument calibrations for radiation dosimetry, medical diagnostics and treatment, smoke detectors, devices for environmental monitoring, semiconductor wafer characterisation, etc. Even a relatively small improvement in the accuracy for the end users, as a result of the shortened calibration chain targeted in this project, will generate a very significant amount of economic benefit for the EU. In the technology sector, where the benefit-to-cost ratio of electrical measurements is amongst the highest, the development of new types of devices, sensors, and measurement methods with faster speed, higher sensitivity, and lower energy consumption, will become possible.

The long-term environmental impact of this project will be indirect, yet strong; many measurement techniques, be they environmental, medical or scientific, make use of transducing elements based on capacitance. Improving the traceability to capacitance will improve the sensitivity and reproducibility of such measurement techniques, leading in turn to improved data quality which will lead to several benefits: more efficient engines, a reduction in exhaust gases, the measurement of polluting particulates, and to an improvement in electrical impedance spectroscopy for geophysics, to name only some. The political benefit of the research will be that a high-end primary standard will become attainable for almost every metrology or calibration laboratory.

Proliferation of primary quantum standards is one of the key aims of international metrology and it allows all countries to interact on an equal basis.

List of publications

[1] Chae, D.-H., Kim, W.-S. and Park, J. (2020). Realization of 5*he*25he2 with graphene quantum Hall resistance array. *Appl. Phys. Lett.* **116**, 093102 https://doi.org/10.1063/1.5139965

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 June 2019, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Klaus Pierz, PTB Tel: +49 531 592 2412 E-mail: klaus.pierz@ptb.de
Project website address: https://www.ptb.de/empir2019/giqs/home/</td></tr>
<tr><td>Internal Funded Partners:
1. PTB, Germany
2. CMI, Czech Republic
3. INRIM, Italy
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11. KRISS, Korea, Republic of</td></tr>
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