Title: Quantum resistance metrology based on graphene

Abstract

The dissemination of resistance calibration should be improved by developing a quantum Hall resistance standard matching the simplicity of Josephson voltage standards. The new material graphene has unique properties which enable a step improvement in terms of enhanced and simplified dissemination. The improvement will be dramatic, since an operation of the quantum standard at considerably smaller magnetic field and higher temperature will become possible. This paves the way to a robust, simpler to operate and cheaper, yet ultimately precise system for electrical measurements with potential to be used even outside NMIs. The project results will benefit all NMIs and measurement services in Europe, and all industries relying on their service.

Conformity with the Work Programme

This Call for JRPs conforms to the EMRP Outline 2008, section on "Grand Challenges" related to Industry & Fundamental Metrology on pages 10 and 11.

Keywords

Quantum Hall effect (QHE), quantum resistance standard, quantum impedance standard, epitaxial graphene, CVD graphene, direct dissemination of units of the new SI

Background to the Metrological Challenges

The units of electricity play a key role in industrial, scientific and technological applications since the measurement of nearly all other units relies on them at some point. All electrical units are in turn traced to the units of voltage and resistance, which are directly derived from the fundamental constants *e* and *h* by using the Josephson and the quantum Hall effect. The forthcoming change to the SI assigns an even higher importance to these units since the mise-en-pratique for the unit of mass will also depend on them.

In contrast to the Josephson effect, which is used to realise the volt, equipment needed for exploiting the quantum Hall effect, to realise the ohm, is very specialised and expensive, typically costing of order 120 k€ for just the base equipment. Its operation also requires experienced staff and consequently quantum resistance standards are not normally available in smaller metrological institutes or industry.

In the 25 pre-graphene years since the discovery of QHE, metrological accurate quantisation of the Hall resistance has been observed in only two classes of materials – Si-FETs and group III-V heterostructures. However, mechanisms of dissipation at high magnetic fields and QHE breakdown are not well understood in these materials. The AC properties of QHE devices in the kHz frequency range important for the impedance metrology have not yet been studied well enough.

The intrinsic properties of graphene as an electronic material have already been explored experimentally and understood theoretically. In particular, the quantization of Hall resistance in this material in the fundamental units of the von Klitzing constant $R_K = h/e^2$ has been observed. A robust appearance of the quantum Hall effect at rather high temperature is a direct consequence of the unusual band structure with its linear dispersion relation. It leads to the large cyclotron energy splitting which makes this system so much favourable compared to the traditional GaAs heterostructures. It is in essence this one property which makes graphene stand out from all other known materials exhibiting the quantum Hall effect. None of the other state of the art systems promises as much as graphene does.

The most successful scalable graphene fabrication techniques demonstrated so far are chemical vapour deposition (CVD) and epitaxial growth on silicon carbide (G-SiC). CVD graphene has not yet reached the level of quality required for metrology, but there is ongoing work aiming to improve the film quality. The G-SiC technology, which holds strong promise for metrology is not presently available to the European NMI community as a whole. Some NMIs have access to G-SiC through academic collaborations, and some have started their own program to develop the G-SiC technology.

On the atomic level graphene is well studied using scanning tunnelling microscopy. However, little is known about the interface between the epitaxial graphene and the substrate or how the interface structure affects the carrier distribution and scattering in graphene. Patterning of graphene wafers involving lithography and reactive etching is well established, but contacting graphene and its preservation over time are still open issues.

Scientific and Technological 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 JRP-Protocol.

The JRP shall focus on exploiting the unique properties of graphene to realise a quantum Hall resistance standard that is simpler to operate then traditional quantum Hall standards.

The specific objectives are:

1. To acquire the technologies for the growth and characterisation of optimised epitaxial and CVD graphene
2. To develop and fabricate high quality, robust graphene quantum resistance standards
3. To investigate the potential of quantum Hall graphene devices for AC metrology
4. To establish the measurement infrastructure and guideline documents supporting the dissemination of graphene based quantum Hall standards

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. Particular reference can be made to the iMERA-PLUS project T4 J04 ULQHE [1].

The total eligible cost of any proposal received for this SRT is expected to be around the 2.7 M€ guideline for proposals in this call. The available budget for integral Research Excellence Grants is 42 months of effort.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the “end user” community. This may be through the inclusion of unfunded JRP partners or collaborators, or by including links to industrial/policy advisory committees, standards committees or other bodies. Evidence of support from the “end user” community (eg letters of support) is encouraged.

You should detail how your JRP results are going to:

- feed into the development of urgent documentary standards through appropriate standards bodies
- transfer knowledge to the instrumentation sector.
- Transfer knowledge to the European electrical and electronic measurement community

You should detail other impacts of your proposed JRP as detailed in the document “Guide 4: Writing a Joint Research Project”

You should also detail how your approach to realising the objectives will further the aim of the EMRP to develop a coherent approach at the European level in the field of metrology and includes 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 Member States and countries associated with the Seventh Framework Programme whose metrology programmes are at an early stage of development to be increased
- outside researchers & research organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of up to 3 years duration.

Additional information

The references were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] http://www.euramet.org/fileadmin/docs/EMRP/JRP/iMERA-plus_JRPs_2010-06-22/T4.J04.pdf