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12 October 2024

The EMPIR Project GIQS: Graphene Impedance Quantum Standard

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***Abstract*— *GIQS: Graphene Impedance Quantum Standard* is a Joint Research Project of the European Metrology Programme for Innovation and Research (EMPIR). The project objective is to combine novel digital impedance measurement bridges with graphene-based ac quantum Hall resistance standards in a simplified cryogenic environment, to achieve simple, user-friendly quantum impedance standards suitable for primary realisation of impedance units in national metrology institutes, calibration centers, and the industry.**

***Index Terms*—Metrology, impedance measurement, bridge circuits, measurement uncertainty, calibration.**

I. Introduction

GIQS: Graphene Impedance Quantum Standard is a three-year Joint Research Project (code 18SIB07) of the European Metrology Programme for Innovation and Research (EMPIR).

The aim of GIQS is to enable an economically efficient traceability of impedance quantity (resistance, capacitance, inductance) measurements to the definining constants (the Planck constant and the elementary charge) of the revised International System of Units (SI). New and easier to operate measurement bridges, convenient and easier to use graphene quantum standards, cryogenic systems, and methods to combine them will be developed. The overall objective of GIQS is to combine novel digital impedance measurement bridges with graphene-based ac quantum Hall resistance standards in a simplified cryogenic environment, and disseminate the technology to National Metrology Institutes, calibration centers, research institutions and industry. Specific objectives are:

1) To optimise graphene devices for their use in the ac regime under relaxed experimental conditions (temperatures of $4\,\mathrm{K}$ or higher, magnetic fields lower than $6\,\mathrm{T}$);
2) To advance digital and Josephson impedance bridges working in a wide range of impedance and frequency;

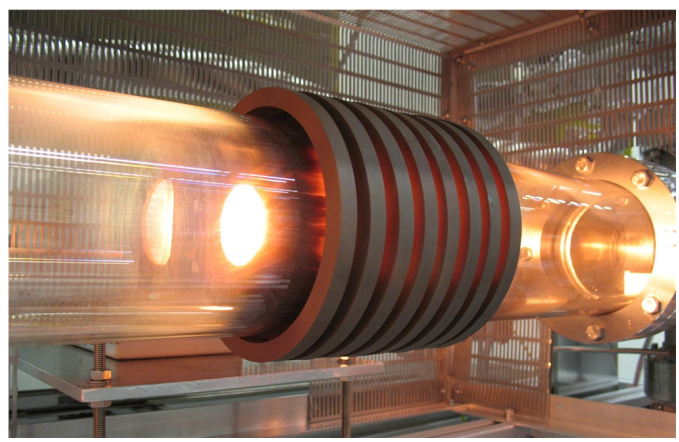

Fig. 1. A furnace for preparation of graphene films by polymer-assisted sublimation (PASG) at $1800\,^{\circ}\mathrm{C}$ for $5\,\mathrm{min}$ in a $1\,\mathrm{bar}$ argon atmosphere.

3) To combine the graphene devices with the bridges developed, and realise a quantum capacitance standard with accuracy in the 10^{-7}–10^{-8} range;
4) To develop a cryocooler system, hosting both Josephson and quantum Hall devices, as the core element of an integrated quantum resistance and impedance standard;
5) To facilitate the take up of the technology and measurement infrastructure developed by graphene manufacturers, standards developing organisations and end users.

This summary is intended as a progress report. More results of the project will be presented at the Conference.

II. Graphene devices

The project is developing quantum Hall devices made of epitaxial graphene grown on silicon carbide; Fig. 1 shows a growth furnace. The target is to achieve a mobility $>$

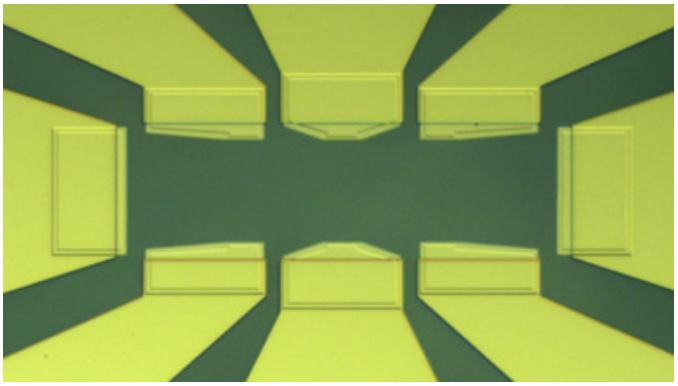

Fig. 2. A graphene Hall bar; the graphene is invisible. The channel width is about $150\,\mu\mathrm{m}$.

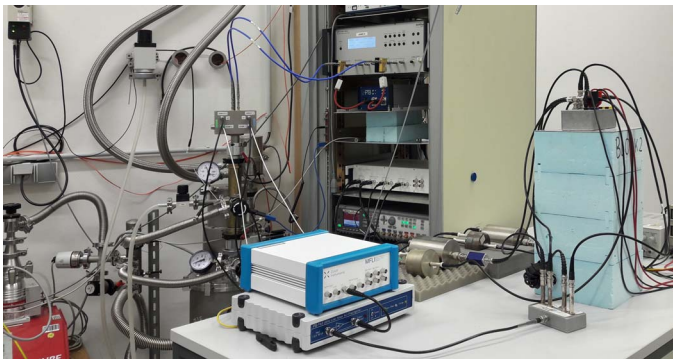

Fig. 3. A four terminal-pair Josephson impedance bridge. The pulse-driven Josephson arrays are operated in a cryocooler (left). The impedance bridge, including all detectors, the capacitance standards under test and the low noise pre-amplifier, is on the table. The rack holds the Josephson array electronics.

$1 \times 10^4\,\mathrm{cm}^2/\mathrm{Vs}$ and a carrier density $< 10^{11}\,\mathrm{cm}^{-2}$ at low temperatures. Special device geometries, suitable for the ac regime, are being designed. The devices (Fig. 2 will be characterised in the dc and ac regime, in the kHz range.

III. Digital bridges

The project is developing fully-digital bridges that can compare the quantum Hall resistance with an artifact impedance standard in the audio frequency range. Two different kind of bridges are under construction:

- Dual Josephson Impedance Bridges (DJIB) [1], [2]. In these bridges (Fig. 3 the reference arm is given by a two-channel Josephson Array Waveform Synthesizer (JAWS) which generate two sinewaves having highly stable and precise amplitudes being based on a quantum effect, as well as high resolution and stability of the relative phase angle. The uncertainty target is in the 10^{-8} range.
- Electronic fully-digital bridges [3], [4]. These (Fig. 4) rely on precise electronic polyphase synthesizers based on digital-to-analog converters. The uncertainty target is in the 10^{-7} range. Specialised bridges to link capacitance to QHR have been assembled and first experiments are ongoing.

IV. Cryogenic environment

Graphene devices show perfect quantisation at lower magnetic fields and higher temperatures than gallium arsenide

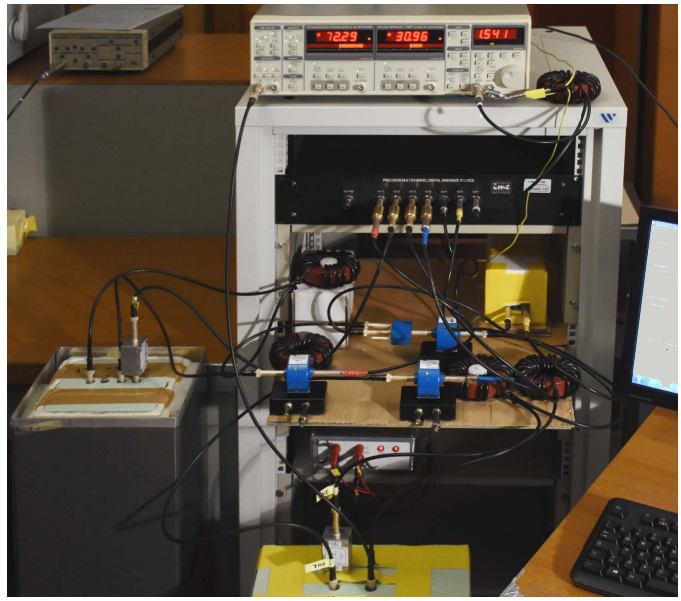

Fig. 4. A fully-digital electronic impedance bridge. The bridge, under development, is intended to compare the quantum Hall resistance with a $8\,\mathrm{nF}$ capacitor, at the frequency of $1541\,\mathrm{Hz}$, with an accuracy in the 10^{-7} range.

devices, thus allowing the use of simpler and smaller cryomagnets, and also a cryogen-free operation. The operation of the device in the ac regime, however, require coaxial connections and special device shielding techniques to minimize the effect of stray capacitances. Mechanical refrigerators can generate (through electromechanical coupling) interferences in the bridge network, which must be properly rejected.

V. Impact

The project is involving stakeholders worldwide in academy, research centers and the industry. Regular updates about the project are posted on the project webpage, `ptb.de/empir2019/giqs` and a LinkedIn group, `linkedin.com/groups/8824119`.

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