Enabling ultimate metrological Quantum Hall Effect (QHE) devices

EURAMET
European Association of National Metrology Institutes

The need for the project

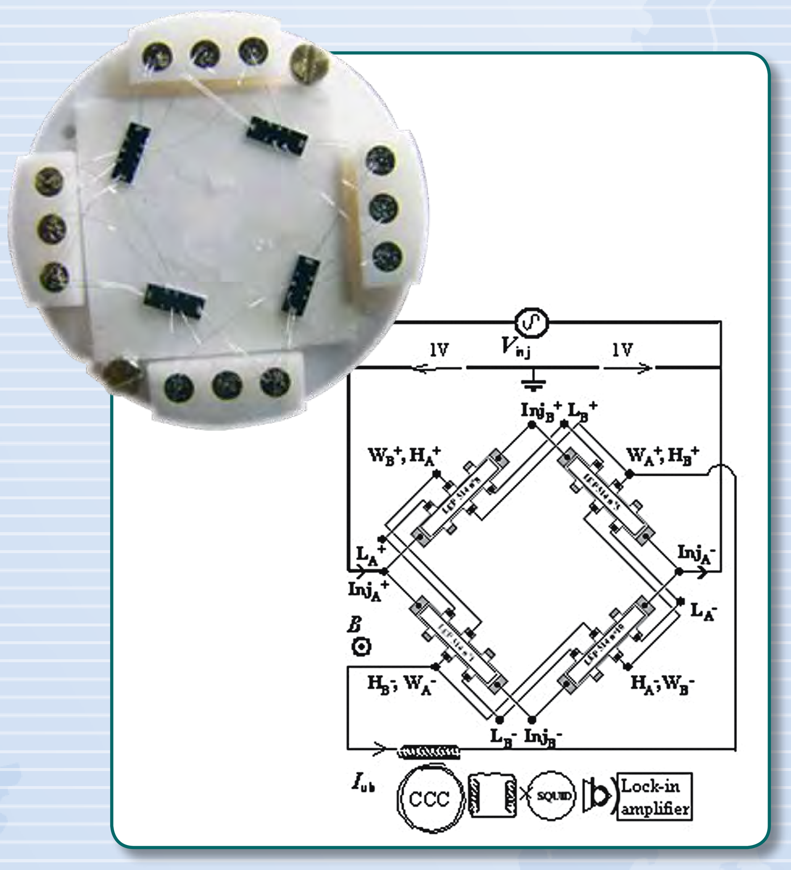
The Quantum Hall Effect (QHE) has been the official representation of the electrical resistance unit since 1990. It provides a quantised resistance which is dependent on the electron charge and Planck constant. It is extremely reproducible, with typical uncertainties as low as 10^{-9} and provides the ability to link the ohm (Ω) to fundamental physical constants.

This project aimed to deepen the understanding of QHE and develop the next generation of QHE based resistance standards with improved performances that match current industrial needs. This includes developing QHE standards, making them easier to use and implement, at reduced costs, and establishing a wide quantised resistance scale ideally from 100 Ω – 1 MΩ.

To do this, the project aimed to investigate new devices (Quantum Hall Arrays (QHARS)) and the use of novel materials, such as graphene in QHE devices.

Technical achievements

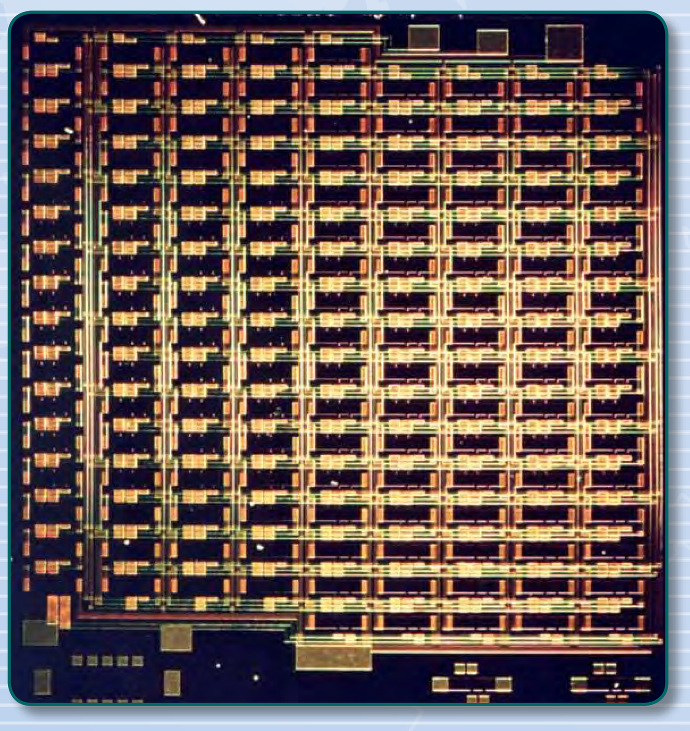
The uncertainty of QHE in Gallium Arsenide (GaAs) (commonly used to fabricate QHE-based resistance standards) was demonstrated to be as low as 3×10^{-11}, one order of magnitude lower than the previous best quantisation tests. This was done using the quantum Wheatstone bridge technique.



Reproducibility test of the QHE in GaAs samples by means of the quantum Wheatstone bridge technique. 1) Picture of the device. 2) Drawing of the experimental principle.

The quantisation of the Hall resistance in the fractional QHE regime was carried out for the first time in high mobility ($10^7 cm^2/V/s$) GaAs (accuracy within 3×10^{-8}).

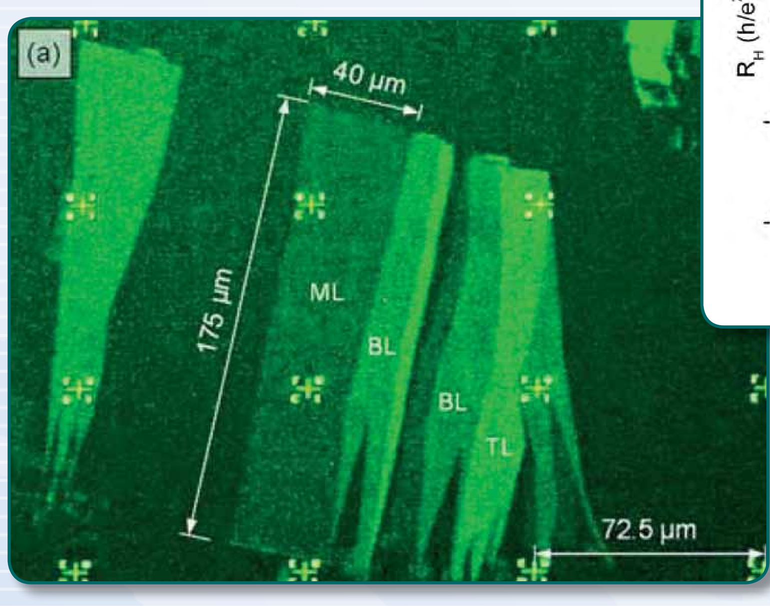
The project pioneered the development of a reliable fabrication process of QHE devices adapted for metrological measurement from graphene exfoliated from graphite, although some limitations were found.

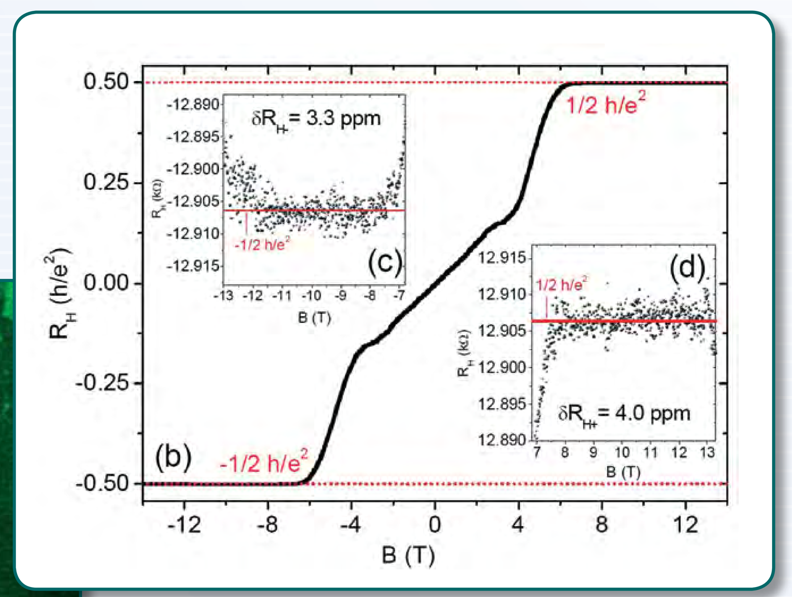


Picture of a 100 W QHARS (129 Hall bars in parallel with 16 Hall bars in series). The Hall bars are 400 µm wide. The total size of the device is 12 mm.

The project has validated the use of low value QHARS as the next generation of quantum resistance standards. These devices, based on a combination of up to 145 Hall bars in series and/or parallel arrays, have been demonstrated to present quantised resistance values ranging from 100 W to 1.29 MW within uncertainties as low as 10^{-9}. The QHARS are compatible with commercial bridges and can be used to calibrate them. During the QHARS fabrication, a process for producing double vertically stacked two dimensional electron gas (2DEG) from GaAs was also successfully developed.

▼ *Optical microscopy image of graphene flakes exfoliated from graphite and deposited on GaAs/AlAs substrates.*





▲ *QHE observed in a monolayer graphene-based Hall bar.*

Supporting the redefinition of SI units

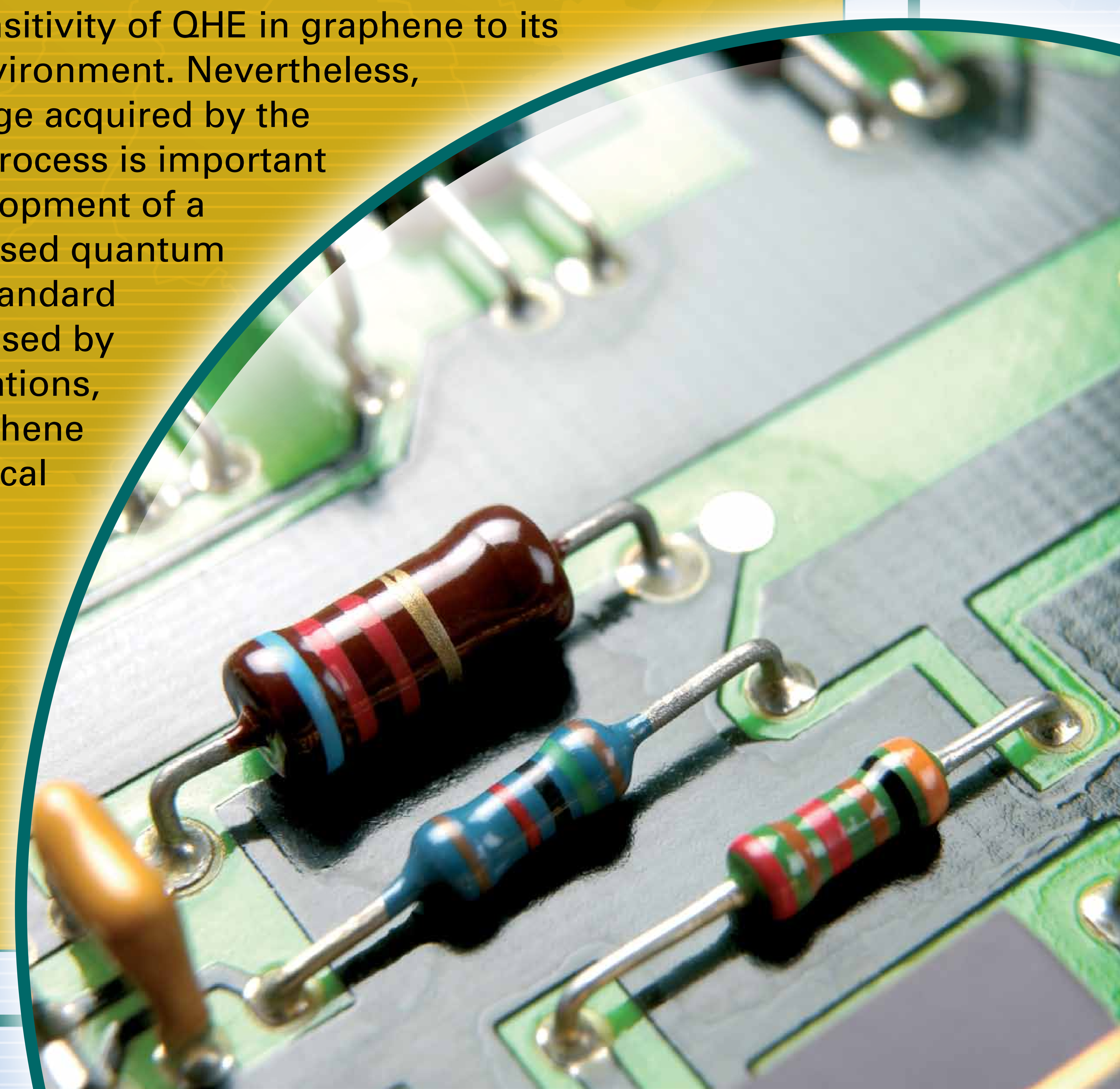
Demonstrated the reliability and robustness of QHE and its underpinning theories by reducing the measurement uncertainty. As a consequence, the project reinforced support for its use in the redefinition of the SI units e.g. the Planck constant (with the watt balance experiment) and the electron charge (with the electron charge quantum metrological triangle experiment).

New quantum resistance standards

Validated the use of QHARS as quantum resistance standards. Guidelines for the use and design of QHARS are to be targeted for National Metrology Institutes as the end-users of QHARS devices.

New graphene fabrication process

Developed a new fabrication process for QHE devices using exfoliated graphene. However, the results of the project also demonstrated that exfoliated graphene may not be the ideal choice for the application of QHE to metrology, due to low yield, the small size of the devices, moderate quality of the metallic contacts on graphene, and high sensitivity of QHE in graphene to its chemical environment. Nevertheless, the knowledge acquired by the fabrication process is important for the development of a graphene-based quantum resistance standard and can be used by other applications, such as graphene use in chemical detectors.



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EMRP
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