Comparison Between GaAs and Graphene QHR Standards for Resistance Realisation at SP

Tobias Bergsten and Gunnar Eklund
SP Technical Research Institute of Sweden

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Tobias Bergsten[1] and Gunnar Eklund
SP Technical Research Institute of Sweden, Box 857, 501 15 Borås, Sweden
[1]tobias.bergsten@sp.se

***Abstract*—We report the first precision QHR measurements at SP using a graphene chip. We compare the results of a resistance calibration using GaAs based chips with the results using a graphene chip. The results agree within a few parts in 10^9 for calibrations of 100 Ω and 10 kΩ resistors. Consistency checks indicate that the uncertainty is lower with the graphene chip, and the noise level is slightly lower. The measurements with the graphene chip were performed exclusively at 4.2 K, which simplifies the calibration procedure considerably compared with GaAs chips.**

***Index Terms*—Calibration, graphene, quantum Hall effect, resistance standard.**

I. Introduction

The SI unit for electrical resistance, the ohm, is realised in National Metrology Institutes (NMI) using the quantum Hall effect. However, the setups for quantum Hall resistance (QHR) are complex, and many NMIs do not have the capacity to run these systems, and therefore send their resistance standards to other labs for calibration, resulting in higher uncertainties. Some NMIs, such as SP, are using ^{4}He systems, which can not utilise the full potential of QHR.

The most commonly used material for the QHR chips is a GaAs based heterostructure. This material requires a very low temperature (preferably below 1 K) and a strong magnetic field (around 10 T), and the equipment is complex and expensive. For the last few years, graphene has been investigated as an alternative material for QHR chips. [1], [2] With graphene, it is possible to use higher temperature (liquid helium, 4.2 K) and lower magnetic field (less than 5 T) [3], and the required equipment would be much simpler.

SP participates in the EMRP project GraphOhm [4], which aims to develop practical QHR standards using graphene. As part of this project, we have performed resistance calibrations using the SP QHR measurement setup, comparing the performance of our regular GaAs chips with a new graphene chip.

II. The SP QHR Setup

The measurement setup for QHR calibrations at SP consists of a pumped ^{4}He cryostat with a superconducting coil, a cryogenic current comparator (CCC), and computer software for automatic CCC control and measurement. The cryostat can reach about 1.5 K when pumping the sample space, and the superconducting coil can generate a magnetic field up to 12 T. The QHR chip is mounted on a probe which can be inserted in the cryostat while the system is cold. An alternative system with a Josephson potentiometer [5] instead of a CCC has also been developed at SP, but here we have only used the CCC setup.

A number of GaAs QHR chips are available. Most of them need to be cooled to at least 2 K for good performance, but one can be used also at 4.2 K. We use at least two different chips to verify that the results are consistent.

III. Graphene Gating and Characterization

The Hall bar was fabricated from graphene grown epitaxially by SiC sublimation at Linköping University. The material was mostly single layer graphene, with about 20% bilayer patches. We patterned the Hall bars and metal contacts at the cleanroom facilities of Chalmers University of Technology in Gothenburg. The width of the Hall bar was 30 μm and the chip was coated with a 300 nm polymer protective layer.

Initially, the carrier density was 3×10^{12} cm^{-2}, which is too high for QHR measurements. We used the corona discharge (CD) gating method [3] to reduce the carrier density. During the CD procedure, the resistance of the Hall bar was monitored using a multimeter, until a sufficiently high resistance was achieved. We then immediately mounted the probe in the cryostat and cooled it down, in order to preserve the adsorbed charges on the chip surface.

The carrier density after cooldown was 5×10^{11} cm^{-2} and we could observe good quantization of R_{xy} and vanishing R_{xx} at magnetic fields above 8 T. The data in Fig. 1 was measured with two multimeters while feeding a constant current through the Hall bar (43 μA) and sweeping the magnetic field.

IV. Graphene and GaAs Comparison

Comparisons between GaAs and graphene has been carried out before, with extreme precision [6]. Our work is a practical comparison for regular resistance calibrations.

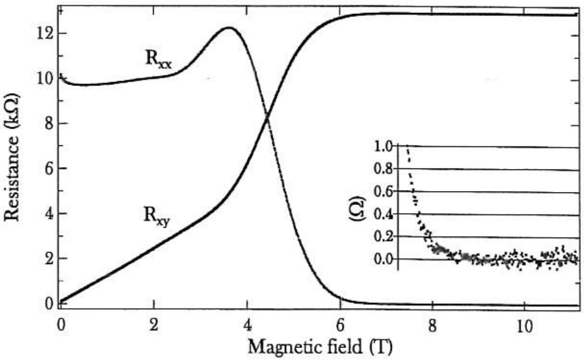

Fig. 1. The longitudinal (R_{xx}) and Hall resistance (R_{xy}) of the graphene Hall bar. The carrier density of the graphene was 5×10^{11} cm^{-2} in this measurement. The inset shows a magnification of R_{xx} as it approaches 0 Ω.

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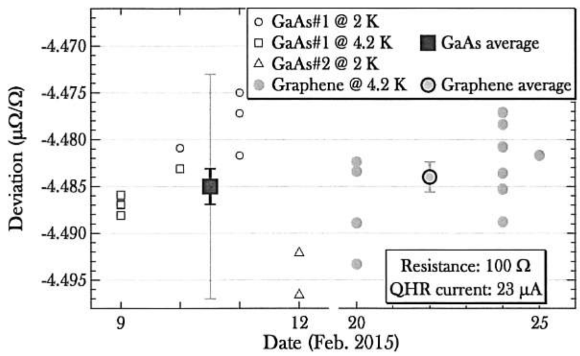

Fig. 2. The relative deviation from the nominal value for a 100 Ω standard resistor, measured with the SP QHR system. The resistor was measured several times during two weeks, first using two GaAs based QHR chips (red open symbols) and then using a graphene QHR chip (green filled circles). The large square and circle with error bars are the average values for the GaAs and the graphene measurements respectively. The short error bars on the averages represent standard deviation of the mean, while the long error bar on the large square is the standard uncertainty for regular QHR calibrations at SP.

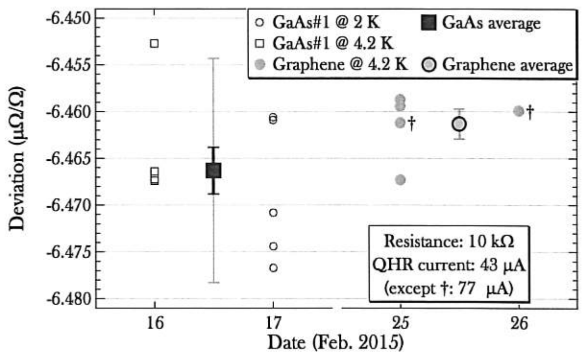

Fig. 3. The relative deviation from the nominal value for a 10 kΩ standard resistor, measured with the SP QHR system. See caption of Fig. 2 for details.

We calibrated two standard resistors using our automated CCC method, one 100 Ω resistor in an oil bath and one 10 kΩ resistor in a temperature controlled box. First we used our regular GaAs QHR chips, varying the magnetic field slightly and using different contacts on the Hall bars. Then we repeated the calibration using the graphene chip, at different magnetic fields. The results are displayed in Fig. 2 and 3.

We see that the results agree well within our standard uncertainty of 12 nΩ/Ω for our system with GaAs chips. This uncertainty is dominated by a possible slope in the resistance plateau, caused by the temperature of the system. Since our setup can only go to about 1.5 K, the temperature is a limiting factor for our calibration uncertainty.

We also did a consistency check by measuring the ratio of the 10 kΩ to the 100 Ω resistors using the CCC (standard uncertainty 3.0×10^{-9}), comparing with the ratio of the resistors measured individually against the QHR. When we used the GaAs QHR results, the relative difference was 8.2×10^{-9}, and the difference was 4.2×10^{-9} when using the graphene QHR results. While this is only a single result, it is an indication that the graphene chip gives better results, and we may be able to lower our uncertainty just by switching to graphene.

For the 100 Ω measurements we used 23 μA current for the QHR chip, in order to keep the power dissipation in the 100 Ω standard low (1 mW). For the 10 kΩ measurements, we used a QHR chip current of 43 μA, limited by the critical current in the GaAs chip. However, the critical current in graphene is considerably higher than in GaAs [2], and we can use higher measurement current. Two of the graphene points in Fig. 3 were measured at 77 μA chip current, on different days. We observed lower noise for these measurements and the two measured values differed by only 1 nΩ/Ω.

V. Risk of Sparks When Using CD Gating

When the precision measurements above were finished, we wanted to reduce the carrier density further using the CD gating method, in order to measure QHR at lower magnetic field. We repeated the procedure as before, and initially saw an increase in the resistance. Then there was a tiny spark on the chip, and the resistance dropped and could not be raised again. Inspection in a microscope revealed that the metal wires to the Hall bar had exploded and scattered debris all over the Hall bar. The graphene seemed to have survived, but was too contaminated to use for further measurements.

VI. Outlook

Using a graphene QHR chip with our existing system simplifies the measurement procedure since we can measure at 4.2 K. The first results indicate that we may also be able to reduce our uncertainty, but this needs to be verified with more measurements, which will be presented at the conference. Some practical details such as the CD gating procedure need to be improved, but graphene is a definite improvement for QHR systems.

Acknowledgements

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