Quantum Hall Resistance verification based on a Direct Current Comparator Bridge

Alessio Pollarolo[1], Duane Brown[1], Shiping Huang[1], Andrew Wachowicz[1] and Ryan Brown[1]

[1]Measurements International, 118 Commerce Drive, Prescott, Ontario, K0E 1T0, Canada
alessio.pollarolo@mintl.com

***Abstract* — We describe measurements using a quantum Hall system equipped with a liquefier and a room temperature direct current comparator bridge to transfer the $R_{k\text{-}90}/2$ value of 12906.4035 Ω to a 1 kΩ. Subsequently we scale from the 1 kΩ down to the 1 Ω to an uncertainty of 0.02 ppm.**

Estimates of the relative uncertainties of the quantum Hall effective are compared to the estimates of the older wet quantum Hall effective along with scaling methods will be provided in this report and a discussion of the advantages of the scaling paths.

***Index Terms* — quantized Hall resistance, traceability, cryogenic current comparator, direct current comparator, standard resistor.**

I. Introduction

The Quantum Hall Effect observable in two-dimensional electron gas relates the dc resistance quantum (QHR) to only fundamental constants of nature [1] as follows

$$R_H = \frac{h}{e^2 i}$$

where h is the Plank constant e is the elementary charge and i is the filing factor that can take integer or fractional values.

Since 1990 the recommendation of the International committee of weight and measurement (CIPM) has been the adoption of the von Klitzing constant, for $i = 1$ as the conventional value to establish the reference standard of resistance. Its value is

$$R_{\text{k-90}} = 25{,}812.807\ \Omega$$

Nowadays the most stable and reliable technology to observe the QHR is based on gallium arsenide (GaAs) heterostructure devices [1]. Even though the GaAs technology is very robust, for years there has been a lot of effort to develop graphene one-atom thick planer structure [2-3]. National metrology laboratories (NMI) provide traceability to their thermally stabilized primary resistors by routinely comparing them to sub-multiples of the QHR.

Such comparison measurements are carried out with cryogenic current comparator (CCC) bridges to provide highest measurement accuracy of few parts in 10^9. Nevertheless, these instruments require additional cryogenic equipment and superconductive electronics to operate, leading to additional system complexities and costs for its maintenance and operation.

In the last fifteen years, the Measurement International (MI) direct current comparator (DCC) bridges became a viable alternative to the CCC thanks to the increase in development work, which resulted in improvements in accuracy and stability [4]. Implementing the DCC bridge in the measurement setup thereby effectively reduces the overall cost of operation. Furthermore, a new cryogenic apparatus equipped with a helium re-liquefier and new immersion probe successfully extends the operability and simplification of the system usability.

II. Measurement System

The GaAs sample is mounted on an immersion probe used to lower the chip into a 60 l dewar. The tank was recently equipped with a helium re-liquefier that employ a GM 4 K cryocooler, which provides 1.5 W and 45 W of cooling power at 4.2 K and 50 K respectively. The new system reliquification rate is up to 20 l of liquid helium per day.

Part of the cryogenic system is a 9 tesla super conductive magnet with its power supply, a liquid helium monitor, a temperature controller and a pressure meter.

The National Research Council of Canada fabricated the GaAs wafer, diced it in chips and bounded the samples to TO8 packages. Quantization at $i = 2$ plateau is achievable at a temperature of 1.4 K and magnetic field B of about 7.5 T. The chip critical current is 77 µA.

The measurement part of the system consists of a MI DCC bridge model 6020Q optimized to perform all the standardized tests to ensure good quantization. The bridge maximum ratio is 14:1, which enables direct comparison between 1 kΩ and $R_{\text{k-90}}/2$. To automate the full measurement, range a low contact resistance automatic 20-channel scanner was used.

All the equipment and the measurement procedures are software controlled to facilitate the system operations.

III. Measurement Result

The measurements we report were performed after verifying the correct quantization of the sample [5]. With a bias current of 77 µA the center of $i = 2$ plateau was measured at 7.3 T, followed by the contact resistance (<0.4 Ω) and the dissipation (<20 nV) measurements.

The cryogenic equipment improvements do not come without a certain level of risk, however. In this particular case, it was the vibration introduced by the re-liquefier. No significant influence was identified in the comparison measurements with and without the re-liquefier functioning.

978-1-5386-0974-3/18/$31.00 ©2018 IEEE

A. *QHR vs* 1 kΩ

To evaluate the DCC bridge stability and verify the integration of cryogenic equipment and measurement instruments, we compared the QHR with one of NRC`s 1 kΩ transfer standard. The resistor is initially measured at the National Lab prior to being transported to our facility. The measurement consists of 35 readings repeated 6 times for each of the QHR contacts, V_{xy}(1-2) and V_{xy}(3-4). The first 10 readings of each run are discarded for initial bridge balancing. The results of four set of separate measurement are shown in figure 1.

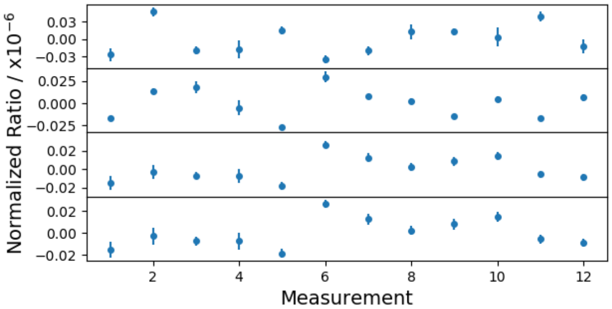

Fig. 1. Normalized ratio in function of measurement reading. The first six measurement are taken using V_{xy}(1-2), whereas the latter six are with V_{xy}(3-4).

For each set of measurements the ratio obtained with V_{xy}(1-2) and V_{xy}(3-4) are averaged together to get the final ratio value, which is communicated to NRC. Table 1 shows the 1 kΩ measured at MI and NRC with their uncertainty ($k = 2$) in the first four columns. The measured values differences and their combines uncertainty are reported in the last two columns.

Table 1. Ratio value between 1 kΩ and the QHR obtained at MI and NRC laboratories. Their difference with the combined uncertainty is also reported.

MI value ×10^{-6}	MI U_C ×10^{-6}	NRC value ×10^{-6}	NRC U_C ×10^{-6}	Difference ×10^{-6}	U_C ×10^{-6}
-9.428	0.008	-9.422	0.007	**-0.006**	**0.011**
-9.354	0.010	-9.377	0.007	**0.023**	**0.012**
-9.371	0.015	-9.379	0.007	**0.008**	**0.016**
-9.444	0.008	-9.422	0.007	**-0.022**	**0.011**

B. *Scaling down*

The system is used to provide traceability to primary resistances as its functionality and accuracy are verified From 1 kΩ calibrated against the QHR three additional decade step are required to measure the 1 Ω primary resistance.

During the calibration against the QHR the bridge set 10 mA in the 1 kΩ resistor. During the scaling procedure a power of < 3 mW was applied during measurement. The currents in the lower ratio value resistor 100 Ω, 10 Ω and 1 Ω are 10 mA, 30 mA and 50 mA respectively.

The four measurements of the scaling are reported in table 2, where one can see the measured value and its statistical uncertainty. The difference between the measured 1 Ω value and its value from the calibration report is also reported in table 2.

Table 2. Results of the scaling from the QHR value to the primary standard resistor.

Resistance Ratio Ω	Meas Value Ω	U_S ×10^{-6}	Standard Val Ω	Difference ×10^{-6}
QHR:1 kΩ	999.9974436	0.020	--	**--**
1 kΩ:100 Ω	99.9999507	0.002	--	**--**
100 Ω: 10 Ω	9.999979780	0.003	--	**--**
10 Ω: 1 Ω	1.0000000023	0.003	**0.999 999 961**	**0.041**

IV. Conclusion

We reported the QHR verification and the result of scaling the quantized resistance for $i = 2$ to the 1 Ω standard resistance using the 6020Q room temperature current comparator bridge.

This work is carried out to identify if the DCC bridge in combination with the new re-liquefier cryogenic can be employed to verify the next generation of QHE sample based on graphene technology. Next requirement will be to demonstrate capability in back-to-back comparison of two QHR sample in the same immersion probe. When the dual GaAs measurement will be demonstrated with this system, then it will be used to measure graphene QHR chip.
More data regarding the vibration effect on quantization and scaling at higher value will be present at CPEM 2018.

Acknowledgement

We thank Carlos Sanchez, Berry Wood, Marlin Kraft and Randolph Elmquist for helpful discussions.

References

[1] K. von Klitzing K, Dorda G and Pepper M, "New method for high-accuracy determination of the fine structure constant based on quantized Hall resistance", *Phys. Rev. Lett.* 45494–7, 1980.

[2] B. Jeckelmann and B. Jeanneret, "The quantum Hall effect as an electrical resistance standard" *Rep. Prog. Phys.* 64 1603–1655, 2001.

[3] R. Ribeiro-Palau, R. F. Lafont, J. Brun-Picard, *et al.* "Quantum Hall resistance standard in graphene devices under relaxed experimental conditions" *Nature Nanotechnol.* 10, 965 (2015).

[4] A. R. Panna et al., "Uncertainty of the Ohm using cryogeni and non-cryogenic bridges", Submitted to CPEM 2018, 2018.

[5] F Delahaye and B Jeckelmann, "Revised technical guidelines for reliable dc measurements of the quantized Hall resistance," *Metrologia, vol. 40,* no 4, pp. 217, 2003.