Calibration of room-temperature ratio bridge with graphene quantum Hall array device.

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***Abstract* — We describe the preliminary measurement conducted to establish a baseline dataset toward a cryogen-free system for quantized Hall resistance (QHR) standard application. This paper illustrates the current state-of-the-art cryogenic system, the quantization verification and ratio measurement between an established GaAs Hall bar and a graphene-base quantum Hall array resistance standard (GQHARS). The technology comparison is carried out with a room temperature ratio bridge.**

***Index Terms* — Measurement, measurement standards, measurement techniques, graphene, measurement uncertainty, precision measurements, uncertainty.**

I. Introduction

Since the redefinition of the International System of Units (SI), the realization of the ohm is achieved through the integer of the quantum Hall effect (QHE) expressed in terms of the von Klitzing constant $R_K = h/e^2$, where h is the Plank constant and e is the elementary change.

Graphene-based QHE chips are becoming the predominant choice for realizing the ohm due to their high temperature and low magnetic flux operability (quantization achievable at a temperature of 4 K and magnetic field as low as 4 T), compared to the predecessor GaAs technology [1].

Recent breakthroughs in graphene and sample fabrication [2] enhanced the technology by improving carrier density stability in air condition, tuneability, and improved device integration. Consequently, those advantages enable the realization of quantum Hall array resistance standard values from 100 Ω to 10 kΩ.

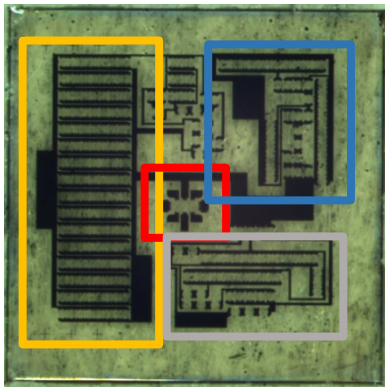

Fig. 1 Picture of a 7 mm × 7 mm GQHARS sample. The red, orange, blue, and gray squares highlight the Hall bar, the 100 Ω, the 1 kΩ and 10 kΩ arrays respectively.

Having multiple GQHARS values ameliorates traceability accuracy when calibrating artifact standards with room temperature ratio bridges. Moreover, combining the latest technology with a cryogen-free cryostat enables a cost-effective and easy-to-use solution for widely adopting the quantum Hall resistance system.

This work compares an established GaAs-based Hall bar QHR to a graphene-based chip with a Hall bar and tree GQHARS, as shown in Fig. 1.

II. Measurement Setup

The GaAs heterostructure sample fabricated at the National Research Council of Canada [3] measures 2 mm × 2 mm. It manifests quantization at $i = 2$ plateau at a temperature of 1.3 K when subjected to magnetic field B of approximately 7.3 T, and its critical current I_C is 77 μA. The chip has six pins, a source, a drain, and two sets of Hall contacts. The graphene-based chip, fabricated by the Research Institutes of Sweden (RISE), is a 7 mm × 7 mm epigraphene grown on silicon carbide (SiC). The precise details of the microfabrication steps are described elsewhere [2]. In brief, we used 120 nm thick superconducting contacts of NbN with a split-contact geometry. [4] The sample is encapsulated using molecular dopants to control the carrier density.

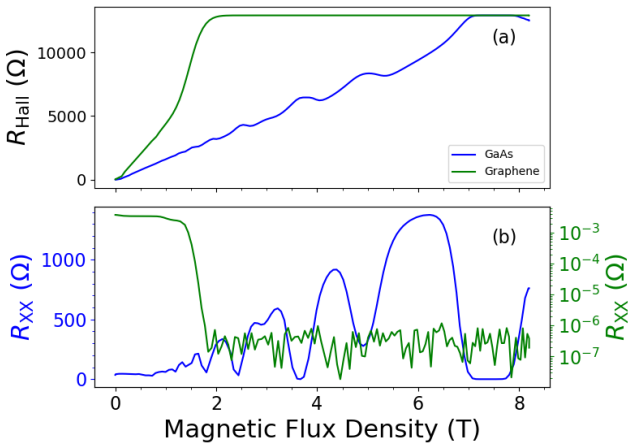

Fig. 2 Sweep test for GaAs (blue curve) and graphene (green curve) samples. The top subplot (a) shows the quantized steps of the Hall resistance, whereas subplot (b) illustrates the longitudinal resistance in function of magnetic flux density for only one pair of contacts.

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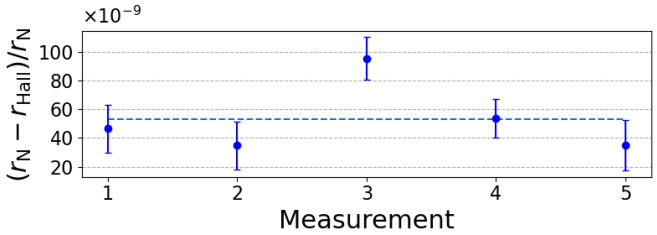

Fig. 3 Ratio between the GaAs and epigraphene Hall resistances. The dotted line is the average of the five measurements.

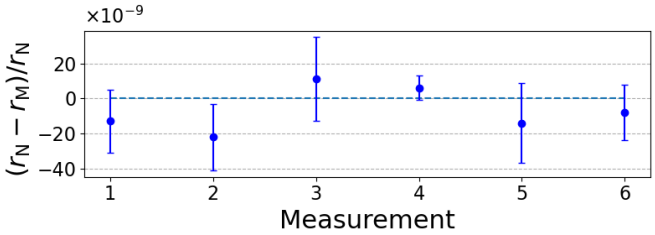

Fig. 4 Ratio between the GaAs Hall resistance and the QHARS 1 kΩ. The dotted line is the average of the measurements.

Fig. 1 shows the die layout, consisting of a Hall bar positioned to the center of the chip, circled in red, and 3 GQHARS of values of 100 Ω in orange, 1 kΩ in blue, and 10 kΩ in gray. All four devices share one common contact point on the chip. Per design [5], the deviation of the array resistance from nominal decade values is limited by the number of element in each array. The approximation is in theory, ~0.2 nΩ/Ω for 100 Ω and ~0.02 nΩ/Ω about for both 10 kΩ and 1 kΩ. The two chips are bonded to a TO8 header. The 10 kΩ is not connected for this work, and only two pairs of contacts are bonded due to limited space in the TO8 header.

The two chips are installed axially on an immersion probe and lowered into a 60 l dewar equipped with GM 4 K cryocooler, which provides 1.5 W colling power at 4.2 K. The system can reliquefy up to 20 l of liquid helium a day. The cryostat, a no-loss system, allows continuous operation at a base temperature of 1.2 K when pumping to its variable temperature insert, reinjecting the gas into the dewar.

III. Measurements

A. Quantization Verification

The quantization is checked for the GaAs device following the guidelines described in [4]. The plateau's center $i = 2$ is measured at 7.5 T (Fig. 2) with a bias current of 77 μA. Subsequently, the contact resistance and the dissipation are measured with a value <0.5 Ω and <20 nV, respectively.

The GQHARS quantization is not possible through a procedure. It is instead verified indirectly by measuring the quantization of the Hall bar. Although the best practices for graphene-based QHE chips differ slightly, the same step as GaAs was executed for simplicity and to have commensurate parameters during sample comparison. With a bias current of 77 μA, comparable values of contact resistance and dissipation are measured.

B. GaAs vs. Graphene Hall resistances

The two technologies' Hall resistances are compared to evaluate the DC ratio bridge stability and accuracy. Fig. 3 shows the ratio r_{HALL} between the GaAs Hall device and the graphene Hall bar normalized to the nominal ratio r_N. Each of he five measurements consisting of 35 readings, of which 25 are averaged. The error bars are the standard deviation of the mean of the readings. Averaging the five measurements establishes the bridge offset that is applied, in this case, 53×10^{-9}, as a correction to the subsequent measurements carried out at a 1:1 ratio.

C. QHARS vs. GaAs Hall resistance

Higher ratio offsets are determined by comparing the GQHARS against each other or the Hall bar. The bridge measurement parameters are set identically to the 1:1 ratio. The bias current is set to 77 μA for Hall resistance, resulting in a 1 mA in the epigraphene 1 kΩ. Fig. 4 shows the measured ratio r_M between the 1 kΩ GQHARS and the GaAs Hall resistance normalized to the nominal value r_N. For this ratio, the averaged offset is 6×10^{-11} with a type A uncertainty of 18×10^{-9}.

VI. Conclusion

We described preliminary comparison measurements between the epigraphene and the GaAs samples. Using GQHARS is an excellent tool for improving the calibration accuracy of standard resistors and DC ratio bridges. We are planning comprehensive measurements of build-up and build-down directly via GQHARS and through resistors with its uncertainty budget. The tests will be part of preparatory work to demonstrate a cryogen-free tabletop system.

Acknowledgment

This work was supported by VINNOVA project 2020-04311, 2021-04177, 2023-00461, and 2023-00991.

References

[1] A. F. Rigosi et al., "Graphene Devices for Tabletop and High-Current Quantized Hall Resistance Standards," IEEE Trans. Instrum. Meas., vol. 68, no. 6, pp. 1870–1878, Jun. 2019, doi: 10.1109/TIM.2018.2882958.M.

[2] H. He et al., "Accurate graphene quantum Hall arrays for the new International System of Units," Nat Commun., vol. 13, no. 1, p. 6933, Nov. 2022, doi: 10.1038/s41467-022-34680-0.

[3] A. D. Inglis, "A Cheaper, Simpler Quantized Hall Resistance Standard", IEEE Tans. Instrum. Meas., vol. 48, no. 2, pp. 289-292, Apr. 1999, doi: 10.1109/CPEM.2004.305570.

[4] F. Delahaye at al., "Revised technical guidelines for reliable dc measurements of the quantized Hall resistance," Metrologia, vol. 40, pp. 217-223, 2023, doi: 10.1088/0026-1394/40/5/302s.

[5] M. Kruskopf et al., "Two-Terminal and Multi-Terminal Designs for Next-Generation Quantized Hall Resistance Standards: Contact Material and Geometry," IEEE Trans. Electron Devices, vol. 66, no. 9, pp. 3973–3977, Sep 2019, doi: 10.1109/TED.2019.2926684

[6] M. Ortolano et al., "On the synthesis of quantum Hall array resistance standards," Metrologia, vol. 52, no. 1, pp. 31–39, 2015, doi: 10.1088/0026-1394/52/1/31.