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Implementation of a 1 GΩ Star-Mesh Graphene Quantized Hall Array Resistance Standard Network for High Resistance Calibration

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***Abstract*—A 1 GΩ star-mesh quantized Hall array resistance standard (QHARS) assembled from 37 individual elements, each exhibiting the quantum Hall effect (QHE), was fabricated and tested. The 1 GΩ QHARS has three orders of magnitude fewer elements than a largely series 1 GΩ QHARS, which would require approximately 77480 elements. A dual source bridge (DSB), using a nanovolt detector and a modified algorithm using least-squares analysis was used to interpolate a bridge null from five measurement points taken near the null of the linear measurement system. The 1 GΩ star-mesh QHARS was used as a standard to calibrate 100 MΩ, 1 GΩ, and 10 GΩ high resistance standards. The star-mesh measurements agreed within the combined standard uncertainties of the values of these standards based on traditional high resistance scaling from the $i = 2$ quantized Hall resistance value of 12906.4037...Ω, where guarded Hamon transfer standards and DSBs are used to build-up to high resistance ranges from 1 MΩ standard resistors.**

***Index Terms*—Bridge circuits, calibration, electrical resistance measurement, graphene, Hall effect devices, resistance, standards.**

I. INTRODUCTION

THE highly favorable electrical properties of graphene have made it the focus of many research pursuits during the past decade or so [1], [2], [3], [4]. When grown epitaxially on 4H-SiC, graphene exhibits a robust quantum Hall effect (QHE) across a wide range of magnetic fields (B-fields) and thus may be conveniently employed into devices for electrical metrology. For these devices to be successfully implemented as standards, the measured resistance must be well quantized [5], [6], [7], [8], [9], [10]. Most epitaxial graphene (EG)-based devices that are used as resistance standards operate at the resistance plateau formed by the QHE at the Landau level $\nu = 2$ ($R_H = h/(\nu e^2) \approx$ 12906.4037 Ω) [11], [12], [13], [14].

Historically, this single value of quantized resistance has constrained the extent to which one may disseminate the unit of ohm. Efforts to expand the access to other quantized values include two main endeavors: 1) using quantized Hall array resistance standards (QHARSs) to link elements in parallel, series [15], [16], [17], [18], [19], [20], [21], [22], [23], or in more general topologies [24], [25] or 2) using p-n junctions [26], [27], [28], [29], [30]. Both approaches enable access to resistances $R = qR_H$, q being a positive rational number, but with the former endeavor being reported more frequently in the scope of metrological objectives. For high resistance values, $q \gg 1$, requiring a large number of devices.

Despite the more frequent usage of EG devices in recent times, a limitation to QHARS fabrication is the total area of high-quality EG, which is currently grown at the centimeter scale [31]. This restriction translates to a very approximate quantized resistance upper bound of 6.5 MΩ (assuming 500 elements in series), which is much smaller than the range of resistances calibrated globally, with some requiring PΩ levels [32].

Transcending this constraint relies on the application of the wye-delta (Y–Δ) star-mesh transformations, an approach that can scale up to high enough values that one meets the limit of meaningful quantized resistances [23], [33], [34], [35], [36]. By utilizing a star-mesh QHARS device designed with the guidance of the mathematical framework presented in [33], a 1 GΩ device is shown in this work to be used as a reference standard for high resistance. The device was tested in conjunction with a new configuration of the NIST dual source bridge (DSB). This combination of quantized device and resistance bridge is a strong potential candidate for replacing the traceability chain for resistances of the same order of

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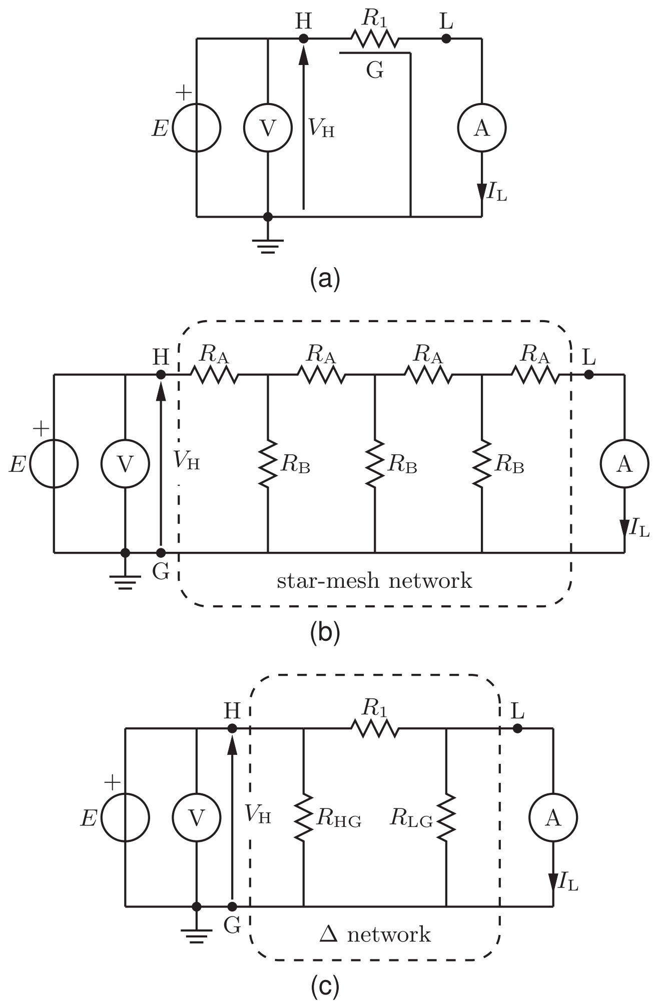

Fig. 1. (a) Measurement schematic for the definition of a three-terminal resistance: R_1 is the measurand resistance with high potential terminal H, low potential terminal L, and the ground terminal G; E is a voltage source; the voltmeter measures the voltage V_H across H and ground and the ammeter measures the current I_L flowing out of L. (b) Three-terminal resistance definition applied to a star-mesh resistance network composed of the series resistances R_A and the parallel resistances R_B. (c) Δ network equivalent to the one in (b).

magnitude as the device output. Furthermore, replacing such long traceability chains (i.e., those requiring several steps to scale up from a single quantized Hall resistance standard) will enable future improvement on precision measurements for higher resistance ranges.

II. STAR-MESH RESISTANCE NETWORK

A. Theory

In this work, resistances are defined as three-terminal standards [37], according to the schematic of Fig. 1(a). The measurand resistance is

$$R_1 = \left.\frac{V_H}{I_L}\right|_{V_L=0}, \tag{1}$$

where V_H is the voltage at the high potential terminal H, I_L is the current flowing out of the low terminal L, and V_L is the voltage at L.

High resistance standards have been implemented in [32], [34], [38], [39], and [40] as Y networks of low resistance elements to improve temperature and humidity stability. Cascading Y networks allows the implementation of *star-mesh* networks.[1] An example of the latter with series resistances R_A and parallel resistances R_B is shown in Fig. 1(b). This can be generally represented by the Δ equivalent network of Fig. 1(c) [42], where the values of R_1, R_{HG}, and R_{LG} can be computed, for example, by iterated Y–Δ transformations [34], [39] (alternative methods of analysis can be found in [43], [44], and [45]). In this Δ equivalent network, owing to the three-terminal resistance definition, the measured resistance coincides with R_1 and the stray resistances R_{HG} and R_{LG} do not affect the measurement.

In a QHARS, R_A and R_B are composed of interconnected elements, each exhibiting the same quantized resistance R_H. As a consequence, $R_1 = qR_H$, where, in general, q is a positive rational number. In order to obtain high resistance values, it is convenient to maximize R_A and minimize R_B. For this reason, this work considers networks in which R_A is composed of elements in series, numbering a, such that $R_A = aR_H$, and R_B is composed of b parallel QHE elements, $R_B = R_H/b$. This choice yields an integer q, minimizing the number of elements at the expense of the possibility of closely approximating a specific resistance value (e.g., decadal values commonly employed in calibrations). To design a star-mesh QHARS with a specific value of q, minimizing the number of elements, one may use the general optimization process described in [33], involving recursive star-mesh transformations. This process, at the level of recursion M, generates a network with an approximate total number of elements given by

$$D_T(M, b, q) = \frac{2^M}{b}(bq+1)^{2^{-M}} - \frac{2^M}{b} + \left(2^M - 1\right) b \tag{2}$$

and with

$$a \approx \frac{1}{b}(bq+1)^{2^{-M}} - \frac{1}{b}. \tag{3}$$

For the optimization, one finds from (2) values of M and b yielding a suitable number $\mathrm{D}_T(M, b, q)$ and from (3) determines a.

A possible solution for a target resistance of 1 GΩ at the level of recursion $M = 2$ is $b = 3$, $a = 7$, and $D_T = 37$. In this arrangement, the elements of the Δ equivalent circuit have values $R_1 = 84847R_H \approx 1.095069$ Ω and $R_{LG} = R_{HG} = (7 + 23/72)R_H \approx 94.46770$ Ω.

B. 1 GΩ Graphene QHARS

The device design followed the configuration proposed in Section II-A, according to the simplified schematic of Fig. 1(b). R_A is composed of seven series-connected elements and R_B is composed of three parallel-connected elements.

The QHARS device was prepared with a procedure similar to that described in [23], [46], and [47]. The graphene monolayer is epitaxially grown on a 4H-SiC substrate and the

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[1] In this work, the term *star-mesh resistance network* denotes a network of resistances whose three-terminal equivalent resistance can be computed by means of recursive star-mesh transformations [38], [41]; in circuit theory, these are more commonly indicated with the term *ladder networks*.

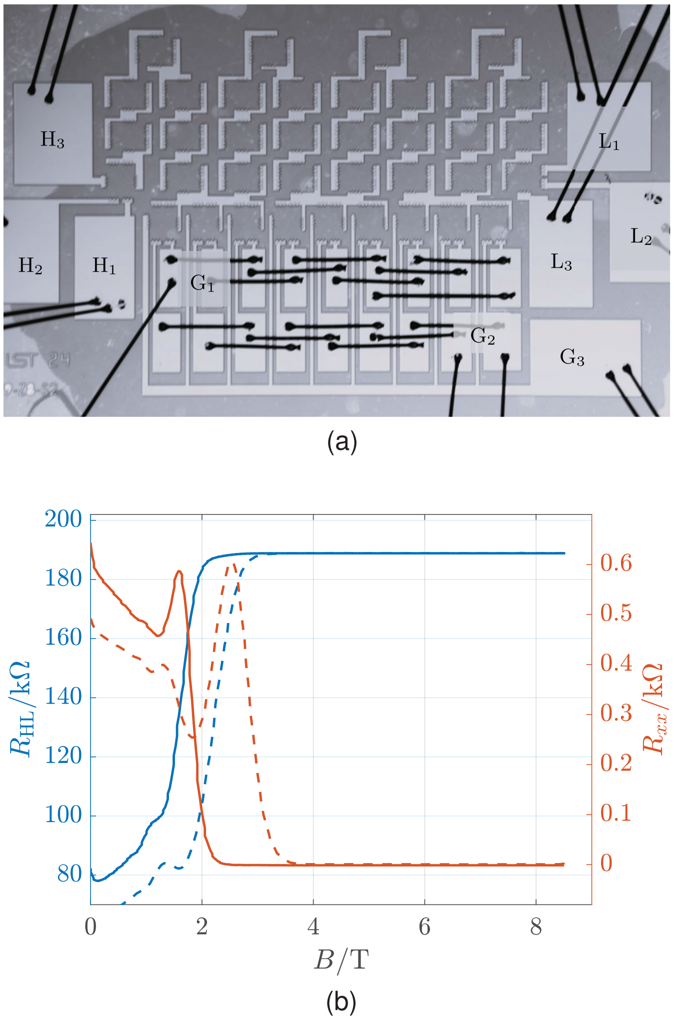


Fig. 2. 1 GΩ device employed in this experiment. (a) Optical image of the 1 GΩ device with the wire bonds at the terminals G$_1$ and G$_2$ to implement the triple series connection. (b) Magneto-transport measurements of this star-mesh QHARS before (solid line) and after (dashed line) annealing to increase the carrier density [52].

monolayer quality is inspected using optical and confocal laser scanning microscopy [48]. Then, a lithographic process is used to fabricate the QHE elements, contacts, and superconducting NbTiN interconnections [31], [49]. The use of superconducting material enables crossover-free interconnections [31] throughout the device, except at the terminal elements, where crossovers are required to facilitate triple connections to a measuring system [15], [50].

The QHARS device fabrication process and graphene growth are described in more detail in our recent articles [23], [47], [51]. The individual QHE elements size is 300μm × 300μm the resulting chip size is approximately 5mm × 3mm.

A photograph of the device is presented in Fig. 2(a). The device has terminals H$_1$–H$_3$, G$_1$–G$_3$, and L$_1$–L$_3$. These allow the interconnection of the QHARS to an external circuit by means of triple connections to minimize the error introduced by the wiring resistances [15]. The QHARS device is mounted onto a transistor outline (TO-8) package.

Fig. 2(b) reports the magnetotransport measurements of the QHARS, obtained by ramping B from zero to 8.5 T at around a temperature of 3 K. The blue curves in Fig. 2(b) represent the resistance $R_{\mathrm{HL}} = R_1 \parallel (R_{\mathrm{HG}}+R_{\mathrm{LG}})$, where $\parallel$ denotes the parallel equivalent resistance, obtained by disconnecting terminals G$_1$, G$_2$, and G$_3$ from ground. When the device is fully quantized, $R_{\mathrm{HL}} \approx 188.9$ kΩ. This resistance was measured by injecting a 1 μA current through the terminals H$_3$ and L$_3$ with a source-measure unit (Keithley 2612A) and by measuring the voltage across the H$_2$ and the L$_2$ terminals with a digital multimeter (Keysight 3458A).

The longitudinal resistance R_{xx} of a single element was also measured, shown in the plot with orange curves. This resistance was measured by injecting a 1 μA current through the terminals H$_3$ and L$_3$ and by measuring the voltage across H$_2$ and H$_1$.

The solid lines represent data taken at a carrier density at which most of the measurements presented in this article were conducted: the QHARS is n-type doped and the carrier density is $n_{\mathrm{e}} \approx 1.4 \times 10^{11}$ cm^{-2}, estimated from the magneto-transport measurement. The dashed lines correspond instead to data collected after having annealed the device, thus increasing the carrier density [52]. In fact, the critical current I_{C} at which the QHE breaks down [53], [54], [55] depends on the carrier density and, for a single device, it has typical values in the range of a hundred μA [7], [19], [22], [54]. For the QHARS, the current through the devices connected to the H node is about V_1/R_{A}. This is the maximum current in the QHARS and should be less than the critical current I_{C}. As a consequence, the maximum applicable $V_1 \approx I_{\mathrm{C}} R_{\mathrm{A}}$ is of the order of 10 V for these conditions.

III. DUAL SOURCE BRIDGE

The DSB is used as the primary measurement technique for the high resistance values at NIST and other national metrology institutes because of its high accuracy and stability [8], [56], [57], [58]. The bridge was adapted from the Wheatstone bridge, employing the automated high resistance bridge method that was first proposed by Henderson [59]. A DSB is a voltage ratio bridge where the two resistors in the main arms of the Wheatstone bridge are replaced by two voltage sources. A simplified schematic of the bridge is illustrated in Fig. 3(a). The voltage sources V_1 and V_2 are two calibrators (Fluke 5730A and 5720A). The sources were calibrated using an automated potentiometer (Measurements International 8000A/8001A) based on a Cutkosky binary voltage divider [60], [61]. The detector D is a 7.5 digit digital nanovoltmeter (Keysight 34420A). The low sides of the two calibrators and the detector are connected to ground.

The measurement sequence can be summarized as follows.

1) The two calibrators are set to zero, $V_1 = V_2 = 0$ V.
2) The bridge offset is determined from a sequence of detector readings.
3) The calibrator voltage V_1 is set to establish the operating current; the calibrator voltage V_2 is stepped around the value $V_2 = -V_1 R_2^{\mathrm{ref}}/R_1^{\mathrm{ref}}$, where R_1^{ref} and R_2^{ref} are the reference values for the standards, in a 1%–10% range. A waiting time is added after each voltage adjustment to let the system reach a steady state.

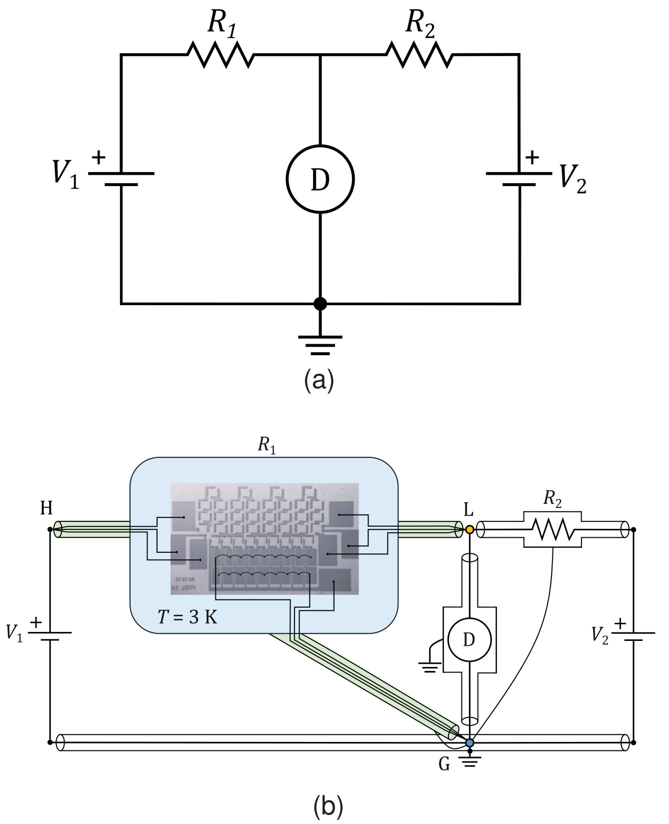


Fig. 3. (a) Principle schematic of the DSB. R_2 is the measurand resistance and R_1 is the calibrated resistance standard. V_1 and V_2 are the output voltages of two voltage calibrators. D is a voltage or current detector. (b) DSB measurement set-up. R_1 is the QHARS device in the cryostat, represented by the light blue rectangle. The ground star point is represented at node G (blue dot) and the detection point is represented at node L (yellow dot).

4) For each voltage V_2, the bridge response is determined from a sequence of detector readings.
5) Steps 1)–4) are repeated by reversing the polarity of the applied voltages.
6) For repeatability, steps 1)–5) are iterated to record a sequence of repeated measurements.
7) The unknown resistance R_2 is determined by least-squares regression according to the measurement model derived in Section IV.

A Visual Basic program was developed to control the bridge, carrying out the sequence of measurement steps automatically.

To confirm the bridge operation and performance before measuring a graphene QHARS, a prototype 1 GΩ room-temperature star-mesh resistance network was compared against a 1 GΩ calibrated resistance standard. The prototype has the same configuration of the QHARS described in Section II and the measurements were performed at several voltages from 10 V to 50 V. Fig. 4(a) shows a picture of the prototype inside its box. This was assembled by combining commercial precision resistors and trimmers to have R_A and R_B [see Fig. 1(b)] as close as possible to the quantized values in the QHARS. The results from the prototype measurements are shown in Fig. 4(b) (the uncertainty bars in the figure represent the standard deviations of the measurements).

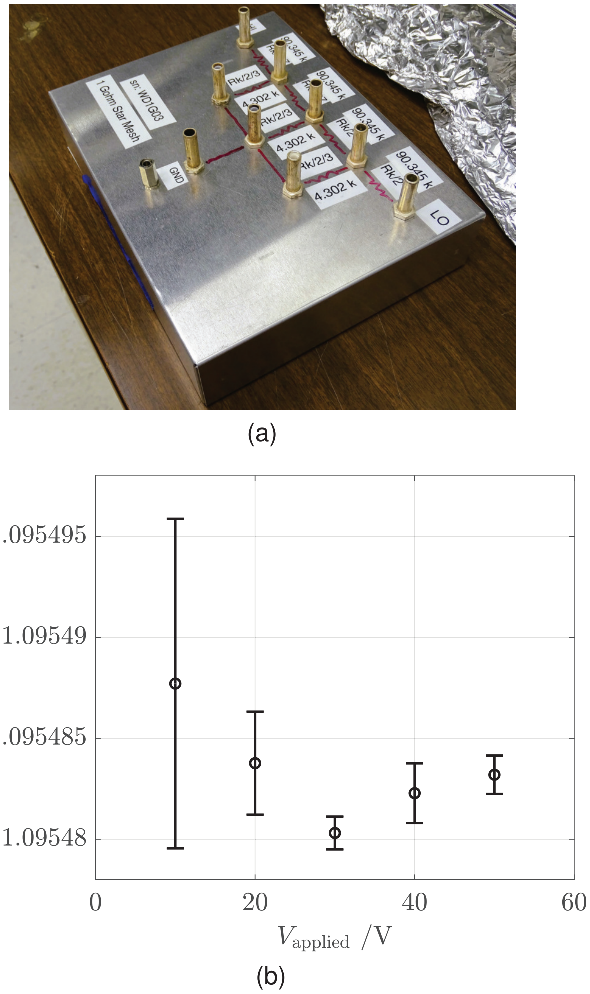


Fig. 4. (a) Picture of the 1 GΩ prototype star-mesh network with the same configuration of the QHARS described in Section II. (b) DSB measurement of the prototype star-mesh network against a 1 GΩ calibrated standard resistor.

The DSB measurements with the QHARS were conducted with the QHARS stored in a wet cryostat, maintained at a base temperature of approximately 3 K and a magnetic field of 8.5 T in persistent mode. The three resistance standards under calibration, with nominal values of 100 MΩ, 1 GΩ, and 10 GΩ, were housed in a temperature-controlled air bath set to 23 °C.

Fig. 3(b) shows an illustrative schematic of the bridge setup, along with the QHARS and the measured resistor. The triple connection to the graphene QHARS is highlighted in the schematic. A junction box was constructed to concentrate all connections to the ground, minimizing interconnection resistances and preventing ground loops. This ground junction box is located in the schematic at node G (blue dot). An additional junction box is inserted at node L (yellow dot) and the H node the three leads join directly at the V_1 calibrator output in a connector. Leads and resistors are shielded to reduce electrical noise.

IV. MEASUREMENT MODEL

The simplest measurement model can be derived from the circuit of Fig. 5, where R_1 is assumed to be a calibrated

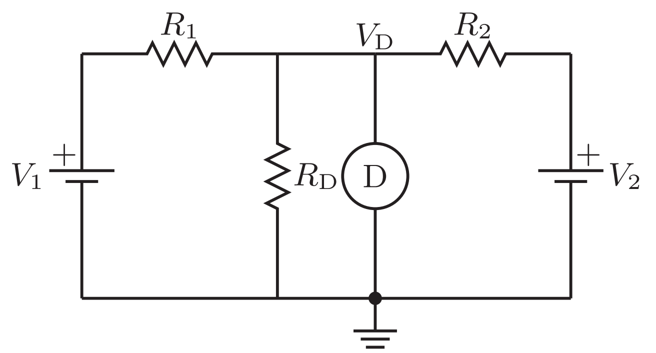


Fig. 5. Equivalent DSB circuit diagram for measurement model. D is a voltage or current detector and V_D is the voltage across it. R_D is the equivalent stray resistance in parallel with the detector.

resistance standard, R_2 is an unknown resistance standard, R_D is the equivalent stray resistance in parallel with the detector, V_1 is set to fix the measurement current, and V_2 is adjusted to find the value V_2^{NULL} for which the bridge is balanced with $V_\mathrm{D} = 0$.

Using Millman's theorem [62], the detector voltage can be expressed as

$$V_\mathrm{D} = \frac{V_1/R_1 + V_2/R_2}{1/R_1 + 1/R_2 + 1/R_\mathrm{D}} \tag{4}$$

from which the unknown resistance can be determined as

$$R_2 = -\frac{V_2^{\mathrm{NULL}}}{V_1} R_1. \tag{5}$$

The detector voltage (4) can be rewritten as

$$V_\mathrm{D} = V_{\mathrm{D}0} + S\,V_2 \tag{6}$$

where

$$S = \frac{1/R_2}{1/R_1 + 1/R_2 + 1/R_\mathrm{D}} \tag{7}$$

is the slope (sensitivity) coefficient and

$$V_{\mathrm{D}0} = \frac{V_1/R_1}{1/R_1 + 1/R_2 + 1/R_\mathrm{D}} \tag{8}$$

is the intercept term. These two parameters can be estimated by linear regression from a sequence of V_D measurements obtained at different values of V_2, from which $V_2^{\mathrm{NULL}} = -V_{\mathrm{D}0}/S$.

Following the procedure described in Section III, the details of the algorithm are as follows. The resistance R_2 is measured N repeated times, and in the following, the data associated with each repetition are labeled with the subscript l, $l = 1, \dots, N$. The lth measurement consists of the following steps.

1) Both calibrators are set to zero to determine the offset and M detector readings $V_{\mathrm{D},jl}^{\mathrm{OS},+}$, $j = 1, \dots, M$, are recorded.
2) V_1 is set to a positive value V_1^+. Accordingly, V_2 is successively set to $2K+1$ voltages $V_{2,k}^+ = V_{2,0}^+ + (k/K)\Delta V_2$, $k = -K, \dots, K$. The center value $V_{2,0}^+$ is chosen from the nominal value R_2^{nom} of R_2 as $V_{2,0}^+ = R_2^{\mathrm{nom}} V_1^+/R_1$ and ΔV_2 is a fixed maximum increment chosen to avoid overranging the detector. For each voltage pair V_1^+, $V_{2,k}^+$, M detector readings $V_{\mathrm{D},jkl}^{\mathrm{READ},+}$ are recorded.
3) Step 1 is repeated obtaining the readings $V_{\mathrm{D},jl}^{\mathrm{OS},-}$.
4) Step 2 is repeated reversing the polarity of both calibrators. For each voltage pair V_1^-, $V_{2,k}^-$, the detector readings $V_{\mathrm{D},jkl}^{\mathrm{READ},-}$ are recorded.

The above recorded data are averaged as $\bar{V}_{\mathrm{D},l}^{\mathrm{OS},\pm} = (1/M)\sum_{j=1}^{M} V_{\mathrm{D},jl}^{\mathrm{OS},\pm}$ and $\bar{V}_{\mathrm{D},kl}^{\mathrm{READ},\pm} = (1/M)\sum_{j=1}^{M} V_{\mathrm{D},jkl}^{\mathrm{READ},\pm}$ and the offset is removed as $\bar{V}_{\mathrm{D},kl}^{\pm} = \bar{V}_{\mathrm{D},kl}^{\mathrm{READ},\pm} - \bar{V}_{\mathrm{D},l}^{\mathrm{OS},\pm}$. To these averages, one can associate the type A uncertainties $u(\bar{V}_{\mathrm{D},l}^{\mathrm{OS},\pm})$, $u(\bar{V}_{\mathrm{D},kl}^{\mathrm{READ},\pm})$ and $u(\bar{V}_{\mathrm{D},kl}^{\pm})$, computed according to the *Guide to the Expression of Uncertainty in Measurement* (GUM) [63].

From (6), the above quantities are related by

$$\bar{V}_{\mathrm{D},kl}^{\pm} = V_{\mathrm{D}0,l}^{\pm} + S_l^{\pm} V_{2,k}^{\pm} \tag{9}$$

where $S_l^{\pm}$ and $V_{\mathrm{D}0,l}^{\pm}$ are the parameters that best approximate the data for a given polarity and l. This set of $2K+1$ equations can be put into the matrix form

$$\boldsymbol{V}_{\mathbf{D}_l}^{\pm} = \boldsymbol{A}^{\pm} \boldsymbol{x}_l^{\pm} \tag{10}$$

where $\boldsymbol{x}_l^{\pm} = [V_{\mathrm{D}0,l}^{\pm}, S_l^{\pm}]^\top$ (where $\top$ denotes the matrix transpose)

$$\boldsymbol{A}^{\pm} = \begin{bmatrix} 1 & V_{2,-K}^{\pm} \\ \vdots & \vdots \\ 1 & V_{2,K}^{\pm} \end{bmatrix} \tag{11}$$

is a $(2K+1) \times 2$ matrix and

$$\boldsymbol{V}_{\mathbf{D}_l}^{\pm} = \begin{bmatrix} \bar{V}_{\mathrm{D},-Kl}^{\pm} \\ \vdots \\ \bar{V}_{\mathrm{D},Kl}^{\pm} \end{bmatrix}. \tag{12}$$

Since the vectors $\boldsymbol{V}_{\mathbf{D}_l}^{\pm}$ have estimated covariance matrices $\boldsymbol{\Sigma}_l^{\pm} = \mathrm{cov}(\boldsymbol{V}_{\mathbf{D}_l}^{\pm})$ equal to

$$\boldsymbol{\Sigma}_l^{\pm} = \begin{bmatrix} u^2\left(\bar{V}_{\mathrm{D},-Kl}^{\pm}\right) & 0 & \cdots & 0 \\ 0 & u^2\left(\bar{V}_{\mathrm{D},(-K+1)l}^{\pm}\right) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & u^2\left(\bar{V}_{\mathrm{D},Kl}^{\pm}\right) \end{bmatrix} \tag{13}$$

and the matrices $\boldsymbol{A}^{\pm}$ have full-column rank, the set of equations (10) can be uniquely solved in the *generalized least squares* sense with the Gauss-Markov estimator [64, Sec. 4.2], and the solutions $\boldsymbol{x}_l^{\pm}$ are described as follows:

$$\boldsymbol{x}_l^{\pm} = \left(\boldsymbol{A}_l^{\pm\top} \left(\boldsymbol{\Sigma}_l^{\pm}\right)^{-1} \boldsymbol{A}_l^{\pm}\right)^{-1} \boldsymbol{A}_l^{\pm\top} \left(\boldsymbol{\Sigma}_l^{\pm}\right)^{-1} \boldsymbol{V}_{\mathbf{D}_l}^{\pm}. \tag{14}$$

The covariance matrices of the solutions $\boldsymbol{x}_l^{\pm}$ are

$$\boldsymbol{\Sigma}_{x,l}^{\pm} = \mathrm{cov}\left(\boldsymbol{x}_l^{\pm}\right) = \hat{\sigma}_l^2 \left(\boldsymbol{A}_l^{\pm\top} \left(\boldsymbol{\Sigma}_l^{\pm}\right)^{-1} \boldsymbol{A}_l^{\pm}\right)^{-1}, \tag{15}$$

where $\hat{\sigma}_l^2$ is estimated by

$$\hat{\sigma}_l{}^2 = \frac{\left(\boldsymbol{V}_{\mathbf{D}_l}^{\pm} - \boldsymbol{A}_l^{\pm}\boldsymbol{x}_l^{\pm}\right)^\top \left(\boldsymbol{\Sigma}_l^{\pm}\right)^{-1} \left(\boldsymbol{V}_{\mathbf{D}_l}^{\pm} - \boldsymbol{A}_l^{\pm}\boldsymbol{x}_l^{\pm}\right)}{2K-1}. \tag{16}$$

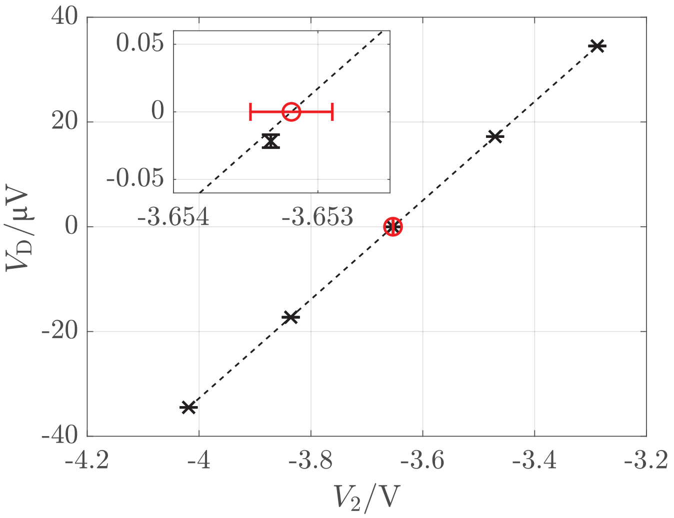


Fig. 6. Example of the method. The black crosses are $[\bar{V}^{+}_{\mathrm{D},-21},\dots,\bar{V}^{+}_{\mathrm{D},21}]$ as a function of $[V^{+}_{2,-2},\dots,V^{+}_{2,2}]$. The black dashed line is the linear fit. The red circle is $V^{\mathrm{NULL},+}_{2,1}$.

The interpolated balance values of V_2 are

$$V^{\mathrm{NULL},\pm}_{2,l} = -\frac{V^{\pm}_{\mathrm{D0},l}}{S^{\pm}_{l}}. \tag{17}$$

An example obtained for $l = 1$, $K = 2$, and $V_1 = 2$ V is shown in Fig. 6.

Using (5), the estimated values of R_2 are

$$R^{\pm}_{2,l} = -\frac{V^{\mathrm{NULL},\pm}_{2,l} - \Delta V^{\pm}_{2}}{V^{\pm}_{1} - \Delta V^{\pm}_{1}} R_1, \tag{18}$$

where $\Delta V^{\pm}_{1}$ and $\Delta V^{\pm}_{2}$ are the error terms associated with the calibrators, as discussed in Section V-B. The two polarities are averaged to obtain $R_{2,l}$.

The final result $\bar{R}_2$ is the weighted average of $R_{2,1},\dots,R_{2,N}$

$$\bar{R}_2 = \frac{\sum_{l=1}^{N} R_{2,l}/u\left(R_{2,l}\right)^2}{\sum_{l=1}^{N} 1/u\left(R_{2,l}\right)^2}. \tag{19}$$

The uncertainties $u(R_{2,l})$ and $u(\bar{R}_2)$ are evaluated according to the GUM [63] and GUM supplement 2 [65] starting from $\boldsymbol{\Sigma}^{\pm}_{\boldsymbol{x},l}$, $\Delta V^{\pm}_{1}$ and $\Delta V^{\pm}_{2}$.

In this work, all the above calculations and the propagation of uncertainty were performed with the help of the MATLAB library METAS UncLib [66].

V. ERROR SOURCES ANALYSIS

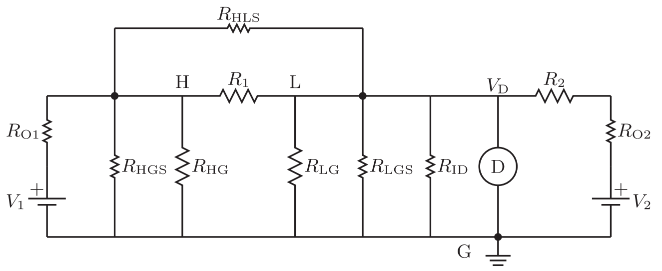


Fig. 7. Equivalent DSB circuit diagram: R_1, R_{HG}, and R_{LG} represent the elements of the equivalent Δ configuration of the QHARS; R_{ID} represents the input resistance of the detector; R_{O1}, and R_{O2} represent the output resistances of the voltage calibrators; R_{HLS}, R_{HGS}, and R_{LGS} represent the stray resistances of the cryostat and cabling. The stray resistors are drawn with smaller size.

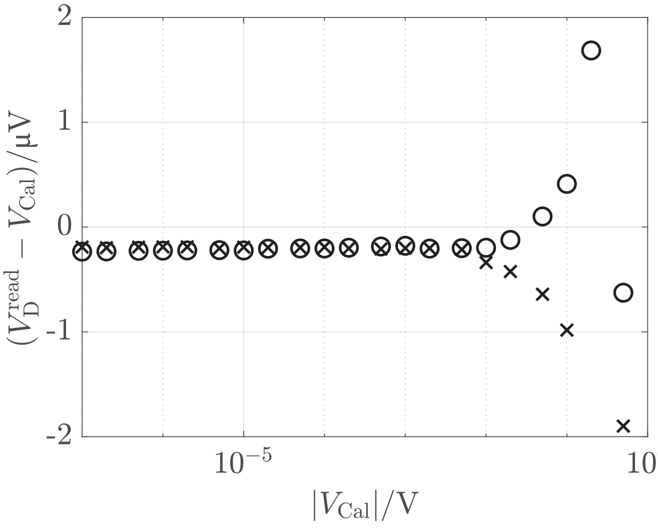


Fig. 8. Study on the linearity of the nanovoltmeter. The vertical scale represents the deviation of the nanovoltmeter reading $V^{\mathrm{read}}_{\mathrm{D}}$ with respect to the calibrator output voltage V_{Cal}, as a function of V_{Cal}, from ±100 nV to ±0.5 V. The circles represent the results for positive V_{Cal}, while the crosses represent the results for negative V_{Cal}.

A complete schematic of the DSB circuit is shown in Fig. 7, where the Δ equivalent circuit of the QHARS is shown. The purpose of this section is to describe which nonidealities of the implemented system can affect the measurement function (19) derived in Section IV, leading to a relative deviation of the measured value $\delta R_2 = (\bar{R}_2 - R_2)/R_2$. Some of these nonidealities are added in the schematic of Fig. 7: R_{ID} represents the input resistance of the detector; R_{O1} represents the output resistance of the calibrator generating V_1 and the contact resistance toward the node H where the triple connection joins; R_{O2} represents the output resistance of the calibrator generating V_2 and the contact and lead resistances of the connections to R_2; and R_{HLS}, R_{HGS}, and R_{LGS} represent the stray (leakage) resistances of the cabling.

A. Detector Error

Since the measurement model described in Section IV is based on a linear interpolation of the zero with offset compensation, the gain and offset errors of the detector are not relevant, but the measuring system needs to be linear. To test the linearity of the nanovoltmeter, the instrument was connected directly to the output of a calibrator, and the calibrator output voltage V_{Cal} was stepped from 100 nV to 0.5 V in a 1–2–5 progression for both polarities. Fig. 8 shows the deviation between the measured voltage $V^{\mathrm{read}}_{\mathrm{D}}$ and V_{Cal}. The results indicate that the nanovoltmeter is linear up to about ±10 mV because the deviation below this limit is virtually constant, for both positive and negative values of the applied voltages.

The detector input resistance R_{ID} is in parallel to R_{LG} and R_{LGS} such that R_{D} in Fig. 5 and in (4) is $R_{\mathrm{D}} = R_{\mathrm{ID}} \parallel$

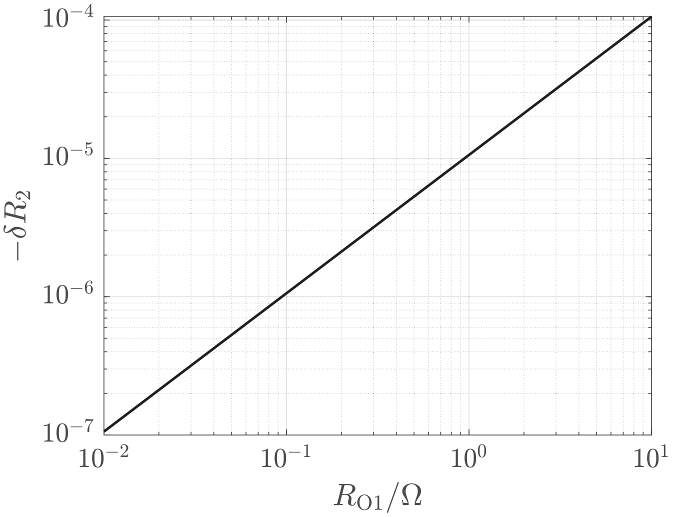


Fig. 9. Analysis of the effect of the calibrator output resistance R_{O1} on the measured resistance $\bar{R}_2$ performed with a Spice model built to mimic the behavior of R_1 in the quantized state.

$R_{LG} \parallel R_{LGS} \approx R_{LG}$. From (4) and (5), this resistance does not cause any systematic error but decreases the bridge sensitivity coefficient S of the bridge.

The detector bias current and the detector offset are compensated by the zero readings and by the polarity reversals described in Section IV.

B. Calibrators

The calibrator errors are taken into account by the terms $\Delta V_1^{\pm}$ and $\Delta V_2^{\pm}$ in (18). These terms are assumed to have zero values with uncertainties $u(\Delta V_1^{\pm})$ and $u(\Delta V_2^{\pm})$ estimated from the calibrators specifications [67], [68]. Since the voltage settings $V_{2,k}^{\pm}$ are in the same calibrator range for any k, $u(\Delta V_2^{\pm})$ does not depend on k.

From Fig. 7, it can be proved that the resistance R_{O1} causes a relative deviation $\delta R_2 \approx -R_{O1}/(R_1 \parallel R_{HG}) \approx (10\ \mu\Omega/\Omega)(R_{O1}/\Omega)$ of the measured resistance $\bar{R}_2$ with respect to R_2, as shown in Fig. 9. To prevent this contribution from being significant, the three leads of the triple connection are joined in a connector directly at the output of the calibrator, yielding a value of R_{O1} at the milliohm level.

The effect of R_{O2} is negligible since it is an additive term to R_2, yielding $\delta R_2 \approx R_{O2}/R_2 < 10^{-8}$.

The resistance R_{O2} is less than 1 Ω, and therefore, the error is less than 10^{-9}.

C. Lead Resistances

The effect of the lead resistances is minimized by the triple connection from the device to the DSB. However, there remains a residual deviation, which was evaluated by means of a Spice circuit simulator according to the methods described in [69]. The effects of the lead resistances connecting the device pads H_1, H_2 and H_3 to the node H and that of the lead resistances connecting the device pads L_1, L_2, and L_3 to L are at the $\delta R_2 \approx 0.1$ nΩ/Ω level and, therefore, negligible. The deviation caused by the resistances R_{lead} of the leads connecting G_1, G_2, and G_3 to node G is shown in Fig. 10. For a measured lead resistance $R_{lead} \approx 3$ Ω, $\delta R_2 \approx 1.6$ μΩ/Ω, which is nonnegligible with respect to the measurement uncertainty.

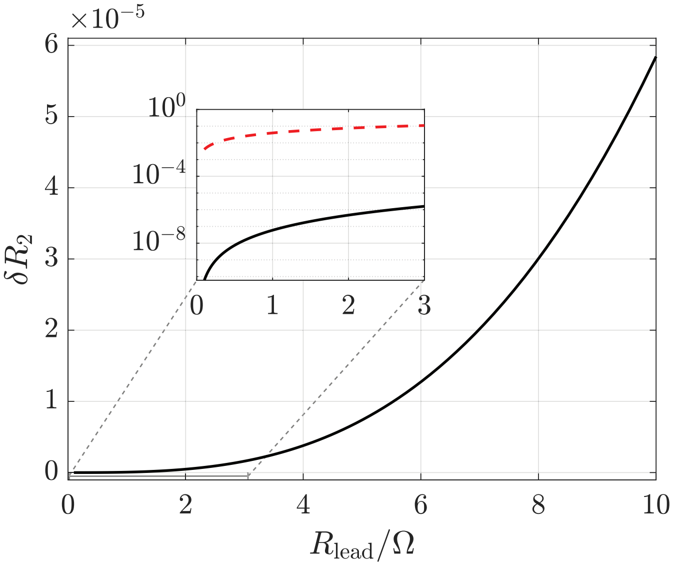


Fig. 10. Analysis of the effect of wires on the measured resistance $\bar{R}_2$ performed with a Spice model built to mimic the behavior of R_1 in the quantized state. R_{lead} is the resistance of each wire connecting the metal pads of the device to the ground located in the air bath outside the cryostat. The black solid line represents a device connected with a triple connection. In the inset, the same line is represented with a vertical logarithmic scale. In addition, the red dashed curve represents a device connected with the three leads in parallel, without taking advantage of the reduction in the contribution of R_{lead} obtained through the triple connection.

D. Stray Resistances

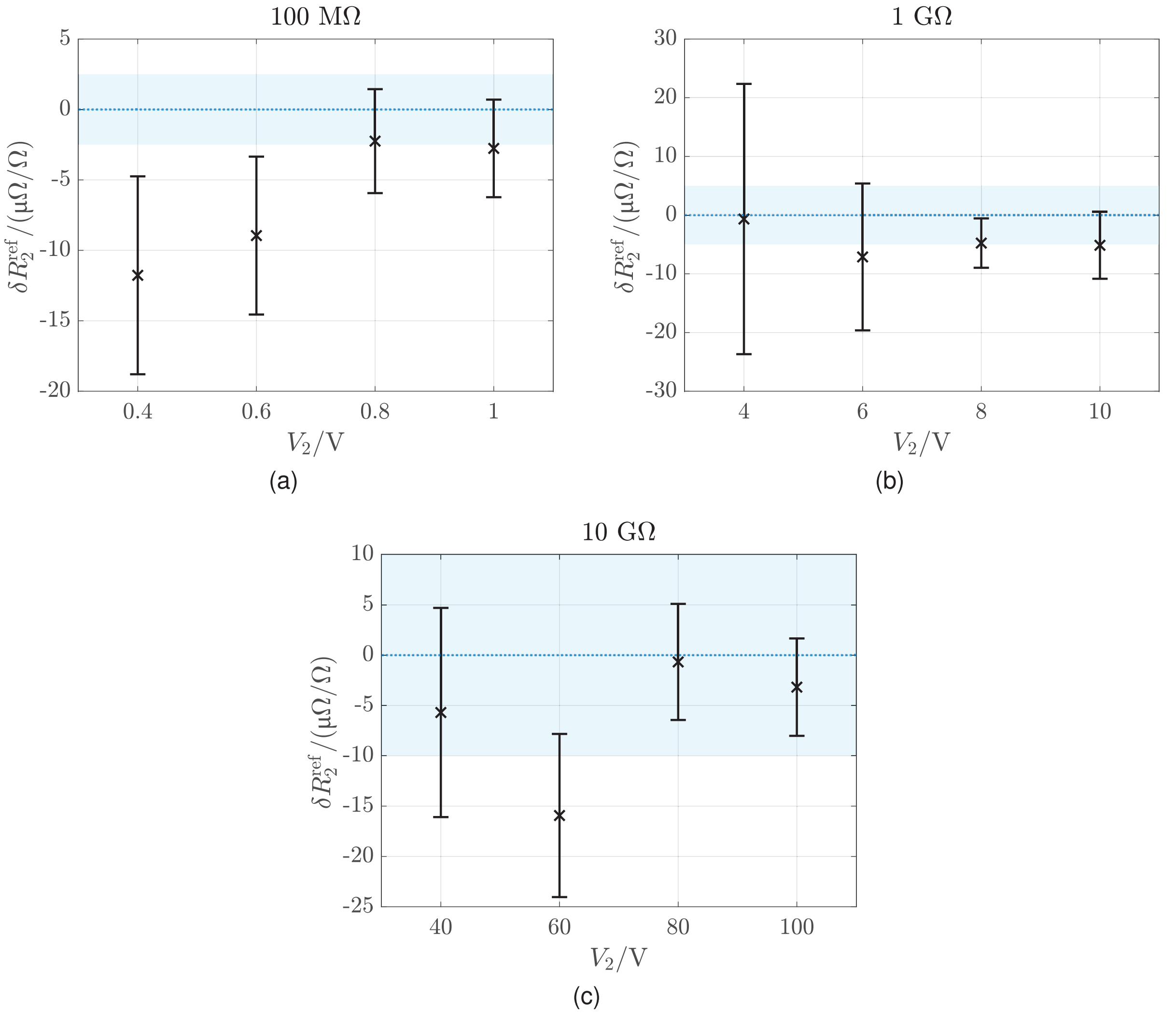
In the present cryogenic setup, there is no guarding circuit and leakage currents can flow through the stray resistances between different terminals. These resistances are represented by R_{HLS}, R_{HGS}, and R_{LGS} in the circuit of Fig. 7. Resistances R_{HGS} and R_{LGS} do not affect the measured value. The resistance R_{HLS} introduces a relative deviation $\delta R_2 \approx R_1/R_{HLS}$ for $R_1 \ll R_{HLS}$. A measurement of the stray resistances yielded values greater than 20 TΩ, limited by the equipment. Therefore, this measurement is only enough to estimate a rough upper bound on the effect of R_{HLS} of $\delta R_2 \approx 50$ μΩ/Ω.

E. Drift in the Measured Resistor

The drift of the three resistance standards is approximately 1.5 μΩ/Ω per year for the 100 MΩ resistance standard, 1.6 μΩ/Ω per year for the 1 GΩ standard, and −2.4 μΩ/Ω per year for the 10 GΩ standard. Therefore, over the timescale of these measurements, the drift of those standard resistors is negligible.

VI. MEASUREMENT RESULTS

The DSB measurements were performed by directly comparing the graphene 1 GΩ QHARS described in Section II with three resistance standards having nominal values of



(a) (b) (c)

Fig. 11. DSB measurement results at different nominal ratios at selected voltages of (a) customer's 100 MΩ resistor, (b) 1 GΩ standard resistor, and (c) 10 GΩ resistor. The DSB measurement result of the 1 GΩ and 10 GΩ resistor were compared against the predicted value of those standards using the historical calibrated data, while the 100 MΩ measurement was compared with the value obtained from NIST primary scale for high resistance standard. The blue region is the estimated combined standard uncertainty associated with the references, obtained from the historical data trend line and from the primary high resistance range.

100 MΩ, 1 GΩ, and 10 GΩ, corresponding to resistance ratios of approximately 10:1, 1:1, and 1:10, respectively.

For accurate high resistance measurements, high voltages are commonly applied across the resistors to minimize noise and interference, typically above 10 V for a 1 GΩ resistor [56], [58], [59]. However, in this case, applying $V_1 > 10$ V results in a current on the order of I_C, which is the breakdown current of the QHARS. For this reason, the voltages V_1 applied to the QHARS were 4 V, 6 V, 8 V, and 10 V, yielding a reasonable signal-to-noise ratio while remaining below the QHARS I_C. The measurement parameters described in Section IV were: $N = 4$, $M = 100$, $\Delta V_2/V_2 = 5 \times 10^{-2}$, and $K = 2$. All measurements were performed with a detector integration time of 100 power line cycles.

The results, presented in Fig. 11, show the relative deviation $\delta R_2^{\mathrm{ref}} = (\bar{R}_2 - R_2^{\mathrm{ref}})/R_2^{\mathrm{ref}}$ between the measured values $\bar{R}_2$ and the reference resistances R_2^{ref} at different applied nominal voltages $V_2 = -V_1 R_2^{\mathrm{ref}}/R_1$. The values R_2^{ref} are obtained from the NIST primary high resistance range, which is traced to a single quantized Hall resistance standard using a cryogenic current comparator and the NIST primary DSB [8], [56], [58]. The 100 MΩ standard was calibrated before and after the DSB measurements, whereas the values for the 1 GΩ and 10 GΩ standards were obtained by extrapolating the historical calibration data. The uncertainty bars represent the combined standard uncertainties of the DSB measurements against the QHARS, while the blue regions represent the standard uncertainties of R_2^{ref}.

Fig. 12 shows measurements on the 1 GΩ device for voltages above 10 V. The black crosses represent measurements taken with a carrier density of about 1.4×10^{11} cm^{-2}, as in Fig. 11, and the breakdown of the QHE is observed at around 12 V, corresponding to $I_C \approx 127$ μA.

To address this, the carrier density was increased to about 2.8×10^{11} cm^{-2} by annealing the device, as discussed in Section II. The DSB measurements at this higher carrier density are represented by red crosses in Fig. 12. The breakdown of the QHE is observed at around 18 V, from which $I_C \approx 191$ μA. At even higher carrier densities, the breakdown can be raised to above 40 V, corresponding to an $I_C \approx 424$ μA.

TABLE I

PRELIMINARY UNCERTAINTY BUDGET FOR THE MEASUREMENT OF FIG. 11(B), FOR V_2 = 8 V

i	Quantity	x_i	$u(x_i)$	Type	c_i	$u_i(x) = \|c_i\|u(x_i)$
1	$V_{2,1}^{\mathrm{NULL},+}$	7.306 94 V	0.000 07 V	A	4.8×10^6 Ω/V	0.32 kΩ
2	$V_{2,1}^{\mathrm{NULL},-}$	−7.306 48 V	0.000 21 V	A	-4.8×10^6 Ω/V	1.01 kΩ
3	$V_{2,2}^{\mathrm{NULL},+}$	7.306 44 V	0.000 02 V	A	3.6×10^7 Ω/V	0.59 kΩ
4	$V_{2,2}^{\mathrm{NULL},-}$	−7.307 02 V	0.000 08 V	A	-3.6×10^7 Ω/V	2.78 kΩ
5	$V_{2,3}^{\mathrm{NULL},+}$	7.306 75 V	0.000 03 V	A	2.6×10^7 Ω/V	0.83 kΩ
6	$V_{2,3}^{\mathrm{NULL},-}$	−7.306 21 V	0.000 09 V	A	-2.6×10^7 Ω/V	2.27 kΩ
7	$V_{2,4}^{\mathrm{NULL},+}$	7.306 20 V	0.000 28 V	A	1.8×10^6 Ω/V	0.51 kΩ
8	$V_{2,4}^{\mathrm{NULL},-}$	−7.307 45 V	0.000 23 V	A	-1.8×10^6 Ω/V	0.41 kΩ
9	ΔV_1^+	0 V	0.000 01 V	B	-6.3×10^7 Ω/V	0.73 kΩ
10	ΔV_1^-	0 V	0.000 01 V	B	6.3×10^7 Ω/V	0.73 kΩ
11	ΔV_2^+	0 V	0.000 01 V	B	-6.8×10^7 Ω/V	0.74 kΩ
12	ΔV_2^-	0 V	0.000 01 V	B	6.8×10^7 Ω/V	0.74 kΩ
13	$R_{\mathrm{lead},1}$	3.0 Ω	0.29 Ω	B	5.3×10^1 Ω/Ω	0.15 kΩ
14	$R_{\mathrm{lead},2}$	3.0 Ω	0.29 Ω	B	5.3×10^1 Ω/Ω	0.15 kΩ
15	$R_{\mathrm{lead},3}$	3.0 Ω	0.29 Ω	B	5.3×10^1 Ω/Ω	0.15 kΩ
	$\bar{R}_2$	1.000 158 9 GΩ		RSS		4.2 kΩ [3.6 µΩ/Ω]

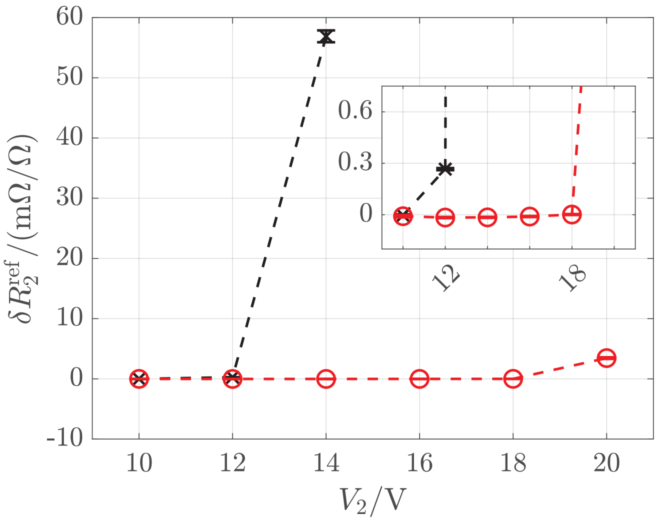


Fig. 12. Breakdown of the QHE observed in the 1 GΩ QHARS occurred at high applied voltages, corresponding to high current bias conditions. The critical current I_C increased with the increment of carrier density n_e (represented by red circles), compared to the lower values observed initially (indicated by black crosses).

The uncertainty budget for the 1 GΩ resistance standard against the graphene QHARS DSB measurement was estimated according to [63]. The measurement was performed at 8 V. The first contributions are the type A uncertainties, at each polarity, of the nanovoltmeter readings for each interpolated balanced values of $V_{2,l}^{\mathrm{NULL},\pm}$. These uncertainties are evaluated and reported in the first eight rows in Table I.

The contributions from rows 9 to 12 are associated with the two calibrators, in which the output voltage errors are evaluated according to the specifications of the instruments [67], [68].

Rows 13–15 are the corrections for the ground lead resistances, which is another significant contribution. This value depends on the wiring inside the cryostat probe and is difficult to reduce even with the triple connection implemented on the QHARS.

The stray resistance R_{HLS} effect, on the other hand, requires more careful investigation to precisely estimate its contribution to the final result.

VII. CONCLUSION

This work demonstrates the feasibility of utilizing a star-mesh QHARS device to generate a 1 GΩ quantized resistance standard. By combining this novel device with a DSB, a robust foundation for a primary resistance standard at the 1 GΩ level was established. This approach has the potential to significantly enhance the accuracy and efficiency of high resistance measurements by replacing lengthy calibration chains of multiple resistance standards and bridges used when scaling from the i = 2 quantum Hall value of 12906.4037...Ω to the MΩ, GΩ, and TΩ resistance ranges. The removal of 5–8 decades of transfer resistance standards in high resistance scaling is an attractive proposition, bringing quantized Hall resistance standards directly to high resistance ranges. Compared to traditional room-temperature standards, the quantized resistance value automatically guarantees stability over time, temperature, and humidity.

QHARS devices, using the star-mesh network beyond 1 GΩ, will use far fewer elements than series arrays but present additional challenges such as considerations in the wiring of probes and choice of materials to suppress stray resistances and leakage currents which can introduce errors to the measurement system. Moreover, a DSB operated with star-mesh networks has reduced sensitivity and increased current noise with respect to one operated with series arrays. The reduced sensitivity is due both to the lower maximum applicable voltage, constrained by the lower resistance seen by the voltage source, and to the low equivalent resistance in parallel to the detector. These limitations also occur with traditional room-temperature Y-standards. As a consequence, the measurement uncertainties so far obtained in this work are of the same order of magnitude as those derived from historical trends, which are generally based on measurements performed by applying up to 100 V. The voltage limitation can be overcome with an asymmetric QHARS design, increasing the resistance seen by the voltage source, allowing to obtain higher sensitivities.

Finally, an important open problem concerning QHARS is the verification of the QHE elements' full quantization. Indeed, a way to verify the full quantization of all individual QHE elements in a QHARS has not been found yet. In this work, the quality of the monolayer graphene was determined by optical and confocal scanning microscopy and the QHARS quantization was assessed by magnetotransport measurements of R_{HL} and of the R_{xx} at accessible terminals. R_{HL} was found to agree with the calculated value of the 37 element QHARS. Moreover, the chosen magnetic field strength is sufficiently high to allow the quantization of all elements even with doping inhomogeneities within the device.

DISCLAIMER

Commercial equipment identified in this article does not imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, nor does it imply that the identified equipment is the best for the purpose.

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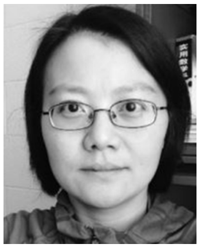

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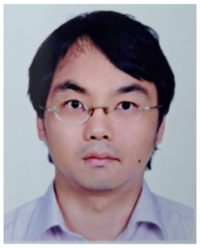
Dr. Newell is a member of the Philosophical Society of Washington, the Chair of the CODATA Task Group on Fundamental Constants, and a fellow of American Physical Society.



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