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Direct Realization of High Resistance Standards Using a Star-Mesh Graphene Quantized Hall Resistance Standard

Ngoc Thanh Mai Tran[1, 2], Marta Musso[3], Wei-Chen Lin[4], Yanfei Yang[1], Alireza R. Panna[1], Cheng-Hsueh Yang[5], Randolph E. Elmquist[1], David B. Newell[1], Chi-Te Liang[5], Massimo Ortolano[2], Albert F. Rigosi[1] and Dean G. Jarrett[1]

[1]National Institute of Standards and Technology, Gaithersburg, MD 20899, USA
[2]University of Maryland, College Park, MD 20742, USA
[3]Politecnico di Torino, 10129 Turin, Italy
[4]National Tsing Hua University, Hsinchu 300044, Taiwan
[5]National Taiwan University, Taipei 106319, Taiwan

***Abstract*—We report a potential application of a 1 GΩ star-mesh graphene quantum Hall array resistance standard (QHARS), consisting of less than forty quantum Hall elements, for high resistance calibration. The QHARS was evaluated and used to calibrate the 100 MΩ to 10 GΩ resistance standards using a dual source bridge with a least-squares interpolation method. The results were compared with the values obtained from long established high resistance calibration chain at the National Institute of Standards and Technology, which is based on the single quantized Hall resistance of 12.906 . . . kΩ, and found to agree within the standard uncertainty of the measurement.**

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

I. Introduction

The graphene material, grown epitaxially on SiC, has shown the quantum Hall effect (QHE) over wide magnetic field ranges, making it suitable for resistance standards. Under suitable magnetic field conditions, typically below 7 T, a single quantum Hall device exhibits a precisely quantized Hall resistance $R_{\mathrm{H}} = h/(\nu e^2) \approx 12\,906.403\,7\ldots\ \Omega$. This realization can be further scaled through the series or parallel interconnection of multiple devices to form a quantized Hall array resistance standard (QHARS), thereby allowing additional access to a wider range of quantized resistance values. However, due to the limited area of uniform, high quality monolayer epitaxial graphene, typically only millimeters in size, practical devices are limited to a maximum resistance of a few MΩ on a single chip.

The star-mesh transformation offers a solution to reach much higher quantized resistance values. Using the model derived in [1], we designed a star-mesh QHARS that produces an approximately 1 GΩ nominal resistance value and demonstrated its use as a high resistance standard as we reported in [2]. A specially configured dual source bridge (DSB) was used with the QHARS to calibrate three artifact standard resistors. The results were then compared with conventional high resistance scales and found to agree within the combined standard uncertainty.

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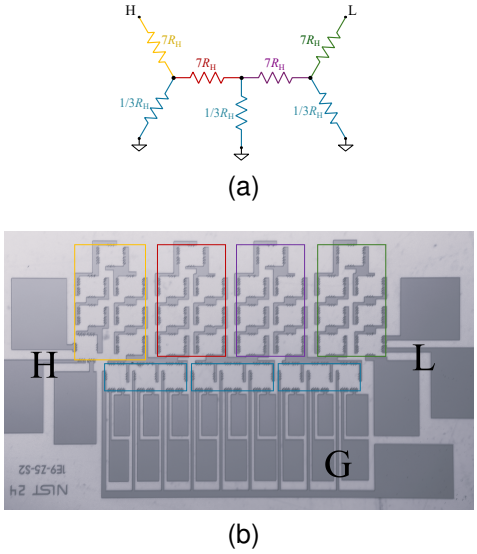


Fig. 1. The graphene QHARS employed in this experiment. (a) The star-mesh network for the 1 GΩ, which was proposed in [1] and (b) its optical image.

II. The Graphene Device

The graphene QHARS employed in this experiment was defined as a three-terminal resistance, with its star-mesh network design based on the optimization processes described in [1], [2] for minimizing the number of elements required to obtain high resistance values. The layout of the Hall elements followed the schematic shown in Fig. 1a. This configuration consists of four sets of seven Hall elements connected in series, with each set connected to a group of three elements in parallel to ground.

The fabrication of the QHARS was reported in [2], [3]. The graphene monolayer was first grown epitaxially on a 4H-SiC wafer, with its quality and uniformity examined by optical and confocal laser scanning microscopy. Lithographic steps were

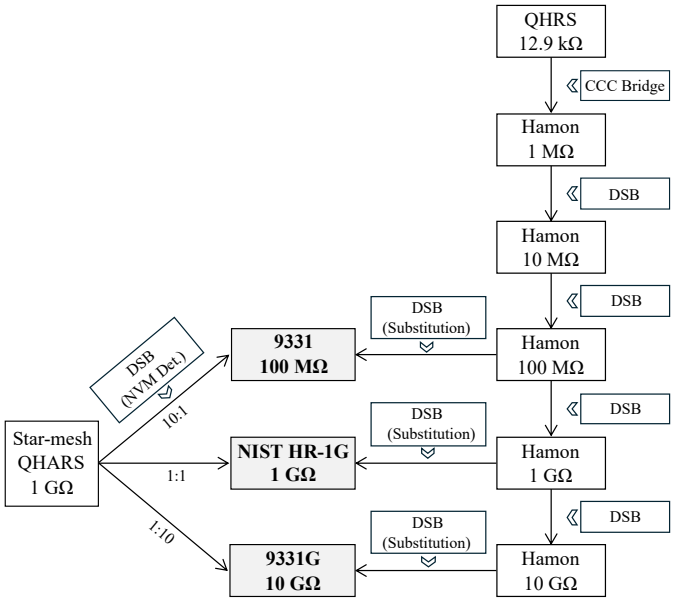


Fig. 2. Traceability chain from the QHE devices to the high resistance standards of 100 MΩ, 1 GΩ and 10 GΩ.

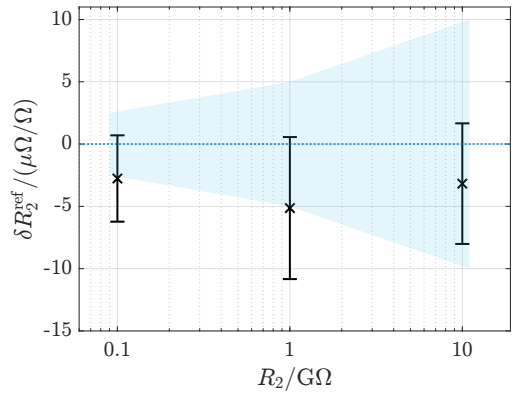


Fig. 3. The DSB measurement results of the three standard resistors against the graphene star-mesh 1 GΩ QHARS at 10 V applied across the QHARS, at different nominal ratios. The results were compared to the one obtained from the NIST primary scale for high resistance standards, as illustrated in Fig. 2.

taken to define the QHR elements, metal contacts, and the superconducting NbTiN interconnections [3]. The superconducting wiring greatly minimizes the internal resistances at the crossing leads [3]. The triple connection [4] was implemented at the terminals (H, L, G) of the 1 GΩ device, where the QHARS was connected to the wiring of the cryostat and the measuring system.

III. Experimental Set-up and Results

The star-mesh QHARS was used in conjunction with a DSB, employing a least-squares method to interpolate the null balance of the bridge [2]. The bridge is adapted from the Wheatstone bridge, where two voltage sources replace the two resistors in the main ratio arms of the Wheatstone bridge. The null detector is a nanovoltmeter. The measurement technique is described in more detail in [2].

Using the DSB, three standard resistors of nominal values 10 MΩ, 1 GΩ, and 10 GΩ were measured by direct comparison against the graphene star-mesh QHARS, corresponding to the resistance ratios R_1/R_2 of approximately 10:1, 1:1, and 1:10, respectively. Here, R_1 represents the QHARS and R_2 are the measured standards. The results were then compared to reference values obtained from the National Institute of Standards and Technology (NIST) primary high resistance range. These reference values were traceable to a single QHR standard using a cryogenic current comparator (CCC) bridge and the NIST primary DSB, as illustrated by the traceability chain in Fig. 2. The DSB measures Hamon transfer standards configured in parallel or series-parallel modes to determine the resistance in series mode. The result in Fig. 3 shows the relative difference $\delta R_2^{\mathrm{ref}}$ between these two values at the voltage $V_1 = 10\,\mathrm{V}$ applied across the star-mesh 1 GΩ QHARS R_1. The uncertainty bars represent the estimated combined standard uncertainty of the DSB resistance measurement traced to the QHARS, while the blue region indicates the standard combined uncertainty associated with the reference values, obtained from the NIST primary high resistance range. The deviation between the two chains may result from stray resistances between different terminals and the voltage source errors.

IV. Conclusion

Star-mesh QHARS shows a promising alternative to currently existing long calibration pathways, offering the potential for improved accuracy in high resistance measurements. The star-mesh 1 GΩ QHARS design uses 1:2000 less components while providing a reliable 1 GΩ quantized resistance reference that, when paired with a dual source bridge, forms a solid structure for providing a quantum standard at the GΩ scale. This approach can significantly enhance both the precision and practicality of high resistance metrology by reducing the need for lengthy sequences of intermediary standards and bridges, which are normally required to scale resistance values from a single QHE device. It also allows multiple high resistance values to be calibrated directly from the quantized Hall resistance references.

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