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Graphene Quantized Hall Array Star-Mesh Network for Improved Bridge Sensitivity

Ngoc Thanh Mai Tran [1,2], Marta Musso [3], Massimo Ortolano [3], Albert F. Rigosi [1], and Dean G. Jarrett [1]

[1] Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA
dean.jarrett@nist.gov

[2] Joint Quantum Institute, University of Maryland, College Park, MD 20742, USA

[3] Department of Electronics and Telecommunications, Politecnico di Torino, 10129 Turin, Italy

***Abstract* — Our recent work on implementing a 1 GΩ star-mesh graphene quantum Hall array resistance standard (QHARS) using a dual-source bridge has comparable measurement results with uncertainties of the same order of magnitude to the well-established measurements based on scaling from a single Hall bar to the MΩ and GΩ ranges, while also revealing certain limitations of the symmetric star-mesh device. The breakdown current in the first branch with few Hall elements, and a low output-to-ground resistance of this QHARS compared to that of the measured standard resistor decreased the bridge sensitivity. These two issues may be overcome by adding a sufficient number of Hall elements at the first and the last branch of the QHARS. The performance of the bridge measurement was then analyzed using a Spice model to replicate the behavior of a star-mesh device in the quantized state. The simulations were performed with a maximum input voltage that the device can withstand. Several improved designs for 1 GΩ, as well as new designs for 10 GΩ QHARS devices, are reported, with device output resistances falling within 500 μΩ/Ω of nominal.**

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

I. Introduction

Recent developments in quantized Hall array resistance standards (QHARSs) have enabled metrologists to begin the query of accessing many quantized resistance values for calibration purposes. These advances were achieved by using graphene configured into on-chip star-mesh transformations [1], [2], [3]. This mathematical equivalence shows that a complex array of interconnected quantized Hall elements behaves as a single, high-value resistor, and it offers immense promise for bypassing the complexities of traditional scaling.

In a star-mesh QHARS, resistance networks become more simplified, offering substantial fabrication relief for values beyond the MΩ level, namely by taking advantage of recursive or multi-stage designs that drastically reduce the number of required Hall elements needed for achieving resistances up to 1 EΩ [2].

This paper proposes a transition from symmetric to asymmetric star-mesh networks to address limitations of breakdown current and bridge sensitivity, by carefully calculating the current in the first branch of the device and the equivalent output-to-ground resistance. These modifications aim to redistribute the internal potential more effectively, thereby increasing the breakdown current threshold of the overall device.

Simulations were performed using high input voltages that are comparable with the NIST high resistance range to test the robustness of the new architectures. We report on several improved designs for 1 GΩ standards and introduce new designs for 10 GΩ QHARS devices. Although these new designs increase the element count from 37 in the symmetric version to 74 in the asymmetric version, the trade-off is justified by potential improvements in bridge sensitivity and higher test voltages, marking a substantial step forward in graphene-based resistance metrology.

II. Limitations of Symmetric Star-Mesh Devices and Solutions

Recent demonstrations of a 1 GΩ symmetric star-mesh QHARS have shown results comparable to established scaling methods [1]. However, these symmetric devices revealed some operational bottlenecks. Specifically, a star-mesh network leads to current distributions that are more likely to result in branch breakdown. During breakdown, a few Hall elements that are subjected to currents exceeding their critical threshold no longer exhibit the dissipationless quantum Hall states. Breakdown has been observed at 12 V for a 1 GΩ QHARS. This low test voltage compared to the 100 V used in the NIST primary high resistance scale, introduced significant current noise, which was identified as the dominant contributor to measurement uncertainty.

Achieving high bridge sensitivity and maintaining a resistance value close to nominal remains a challenge in symmetric configurations due to the low resistance seen by the voltage source and the low equivalent resistance seen by the bridge detector. Therefore, to overcome this issue, an asymmetric design was introduced in which the resistance of the first branch is increased to the required number of elements at high voltage, while the output resistance in parallel with the detector is also maximized. The required number of elements, together with the corresponding critical current, was calculated using an approach similar to that described in [1], and the predicted measurement sensitivity was estimated using equation (7) in the same reference. The measurement performance of each design was subsequently evaluated using a Spice simulator [4], which provides an effective means of estimating sensitivity. Some selected designs with their parameters are summarized in Table 1.

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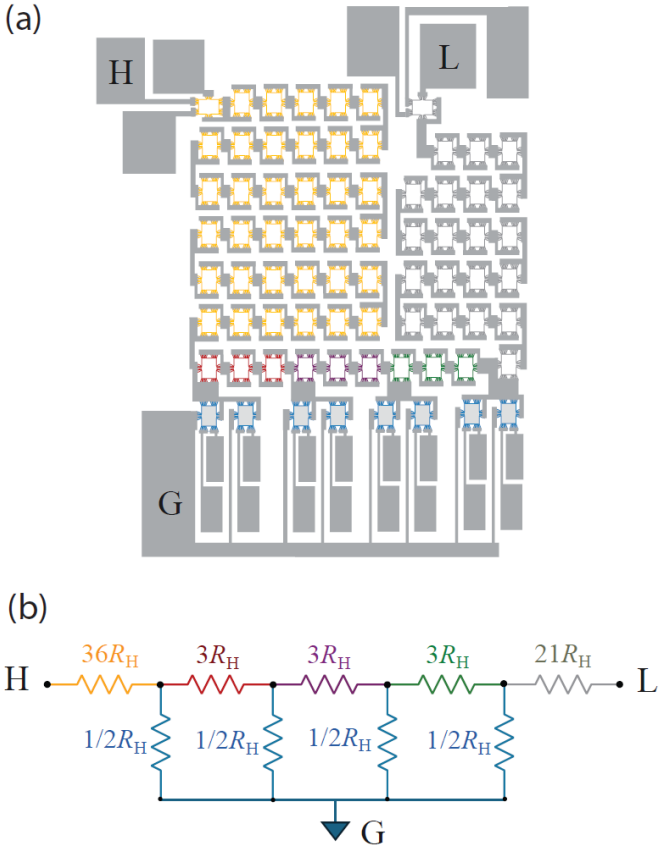


Fig. 1. (a) Asymmetric star-mesh configuration for a 10 GΩ QHARS device divided into color-coded segments. This is a proposed lithographic mask intended for fabricating the first asymmetrical star-mesh graphene-based QHARS device. (b) Schematic of the circuit diagram indicates the exact number of quantum Hall elements needed in each segment and matches the color-coding scheme in (a). 'H' and 'L' refer to the high and low voltage potentials, respectively.

As shown by comparison with the 1 GΩ design, although the optimization algorithm reported in Ref. [2] yields a total of 37 elements for a symmetric star-mesh QHARS, practical constraints associated with measurements using a dual-source bridge require the implementation of twice this number of elements. For the two new 1 GΩ designs shown in the third and fourth columns of Table 1, the critical applied voltage corresponding to an estimated breakdown current is increased to about 100 V, and the sensitivity of both designs is higher than that of the original star-mesh device in the second column. A similar approach is used for the 10 GΩ designs listed in the fifth and sixth columns of Table 1. For the 10 GΩ design in the sixth column, the circuit schematic is shown in Fig. 1, while the proposed lithographic mask layout corresponding to this design is also shown in Fig. 1.

III. Conclusions

This work proposes the new star-mesh QHARS designs to overcome limitations of symmetric device designs for possible improvement in the performance of the bridge measurement. The improved designs for 1 GΩ and 10 GΩ QHARS devices are presented, along with the corresponding calculated bridge sensitivity. In which, the performance of these designs is also verified through Spice simulations.. Overall, one should carefully consider the beneficial trade-off of adding more Hall elements to reduce problems of breakdown current, and these considerations show promise in advancing graphene-based resistance metrology.

Table 1. Description of parameters associated with four different QHARS designs adopting a non-symmetric star-mesh configuration, two designs being valued near 1 GΩ and the other two near 10 GΩ. The equivalent resistance is shown with a corresponding correction to the nearest nominal decade value. Each design also enumerates the total number of Hall elements, a hypothetically applicable voltage, a critical current, and improvement to the bridge sensitivity.

Devices	Original Star-Mesh	1 GΩ (A)	1 GΩ (B)	10 GΩ (A)	10 GΩ (B)
Resistance (GΩ)	1.09507	0.999627	1.00044	9.991712	10.00017
Correction (μΩ/Ω)	95069.6	373.2	439.9	828.8	16.6
Number of elements	37	64	68	71	74
Critical applied voltage (V)	20	100	100	100	100
Critical current (μA)	211.731	239.389	298.968	212.646	259.755
Sensitivity (μV/V)	86.2	276	270	28.2	27.7

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[4] Commercial equipment, instruments, and materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology or the United States government, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.