A Table-Top Graphene Quantized Hall Standard

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***Abstract* — We report the performance of a quantum standard based on epitaxial graphene maintained in a 5 T table-top cryocooler system. The $\nu = 2$ resistance plateau, with a value of $R_{K-90}/2$, is used to scale to 1 kΩ using a binary cryogenic current comparator (BCCC) bridge. The preliminary uncertainties achieved with the BCCC are like those obtained in state-of-the-art measurements using GaAs-based devices. This quantum standard requires no liquid He and can operate continuously, allowing year-round accessibility to traceable resistance measurements.**

***Index Terms* — quantized Hall resistance, epitaxial graphene, binary cryogenic current comparator, direct current comparator, standard resistor.**

I. Introduction

For decades, the National Institute of Standards and Technology (NIST) has provided resistance calibration services using quantized Hall resistance (QHR) standards based on gallium arsenide (GaAs) [1]. The integer quantum Hall effect (QHE) is the foundation for traceability to the *ohm* (SI unit), and although the effect is well-tested [2], accessing the QHR with an uncertainty near one part in 10^9 requires cumbersome and expensive infrastructure to reach low temperatures and high magnetic fields, ultimately limiting the efficiency of calibrations and traceability.

Graphene, the two-dimensional, hexagonal lattice of carbon atoms, exhibits the QHE at higher temperatures and lower magnetic fields than in AlGaAs/GaAs heterostructures [3]. This conceptual realization motivates research in optimizing graphene devices for metrology by using a cryogen-free tabletop system to provide turn-key resistance traceability to the QHR [4]. If coupled with a user-friendly direct current comparator (DCC), such a system would promote accessibility to the QHR for many laboratories at a reasonable level of effort.

The comparison results to be presented here utilize a binary cryogenic current comparator (BCCC) and resistance standards having long calibration histories based on the GaAs standard. Though a BCCC can be used to scale from the QHR $\nu = 2$ plateau ($R_{K-90}/2 = 12906.4035$ Ω) directly to a 100 Ω, 1 kΩ, or 10 kΩ resistor, this work focuses on scaling between the QHR $\nu = 2$ plateau and 1 kΩ. The table-top cryocooler system is mounted on an optical table and attached to a compressor. The cryogen-free system reaches temperatures as low as 4 K and was operated at 5 T for all measurements. The corresponding Type B uncertainties for the BCCC and DCC at the 12.9-to-one ratio are 0.002 μΩ/Ω and 0.01 μΩ/Ω, respectively. Earlier measurements have demonstrated that graphene devices can potentially be used up to 10 V [3, 5], making this technique compatible with high resistance cryogenic current comparators, dual source bridges, and commercial DCC room temperature bridges.

II. Preparation of graphene devices and setup

The graphene-based devices are prepared by methods described rigorously in previous work [5] – [7]. In summary, silicon atoms are sublimated at high temperatures from the SiC substrate, leaving behind carbon atoms comprising monolayer graphene. For device fabrication, the graphene layer is protected by a layer of Pd-Au, etched to create the Hall bar device, and electrically contacted using photolithography. The the carrier density can be adjusted by gentle heating in vacuum or brief exposure to nitric acid vapor to shift the resistance plateau as desired. The Hall contact resistances, measured at 4.5 K, 9 T, and 60 μA, are below 1 Ω.

III. Data and results

A. BCCC Results

Figure 1 shows preliminary results using the BCCC bridge to scale from a graphene device to a 1 kΩ resistor using the following voltages: 0.5 V, 1.0 V, and 1.5 V. Here, the Hall resistances $R_H^{(1)}$ and $R_H^{(2)}$ were measured at two pairs of orthogonal contacts bordering a region of width 0.4 mm and length 0.64 mm. Diagonal measurements between the same contacts were averaged to show the change due to the longitudinal resistance. Contributions to the deviations due to the longitudinal resistance were under 0.01 μΩ/Ω for 38.7 μA and 77.5 μA and averaged 0.02 μΩ/Ω for 116 μA. It is important to note that the 1 kΩ resistor we use for these measurements have been compared to the traditional in-house GaAs QHR, thus providing an indirect basis of comparison between the graphene and GaAs devices.

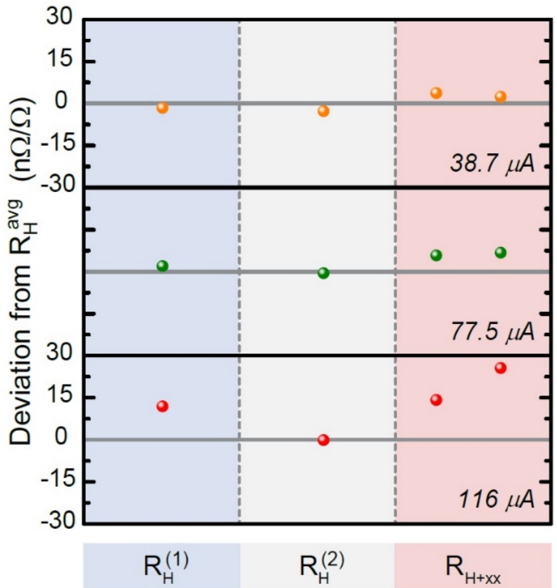
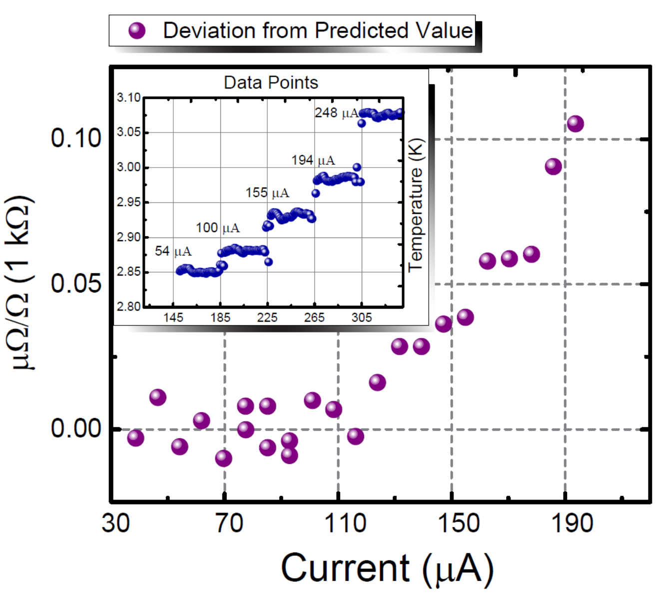


Fig. 1. BCCC measurements show comparisons between the QHR in graphene and a 1 kΩ resistor, using two orthogonal contact pairs corresponding to $R_H^{(1)}$ and $R_H^{(2)}$, and both diagonal contact pairs labelled R_{H+xx} to evaluate the impact of the longitudinal resistance. Type A measurement uncertainties are smaller than the data points.

For 0.5 V and 1 V, corresponding to the currents 38.7 μA and 77.5 μA, the standard deviation of the four orthogonal measurements is 0.0015 μΩ/Ω, and all values were normalized to the average resistance value obtained at these two lower voltages. At 1.5 V, or 116 μA, the deviations are under 0.03 μΩ/Ω. The 1 kΩ resistor drifts at a rate of 0.036 μΩ/(Ω*yr) and has been accounted for in the analysis. The data were collected over a two-week period using a primary winding



count of 2620 and a secondary count of 203. The results support the notion of graphene becoming a reliable QHR standard.

B. Overall Device Performance

Fig. 2. The effect of current on accuracy is shown. Based on these DCC measurements, the graphene QHR sustains its quantized value to within 10 nΩ/Ω up to approximately 116 μA. The current dissipation effect on the sample temperature is shown in the inset. Measurement uncertainties are smaller than the data points.

Current dependence was analyzed with the DCC to demonstrate that the graphene device was able to retain metrologically useful QHR values until at least 150 μA. With future developments, it may be possible to realize a compatibility between these devices and other equipment in resistance metrology.

IV. Conclusion

We have evaluated the performance of a quantum Hall device based on epitaxial graphene by using a BCCC to perform scale-down comparisons to a 1 kΩ resistor and a DCC to characterize overall device performance. These measurements show that graphene is compatible with an experimental setup that requires no liquid He and is accurate to one part in 10^8, enabling future developments for creating systems inherently simpler to use than those for GaAs-based resistance standards.

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