AC and DC Quantized Hall Array Resistance Standards

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Abstract — **Quantized Hall array resistance standards (QHARS) span values from 100 Ω to 1 MΩ and demonstrate precision approaching that of single devices. This paper focuses on QHARS having values near 1 kΩ for increased sensitivity using room-temperature direct current comparator (DCC) bridges and digital impedance bridges. We introduce a dc QHARS design that uses the Wheatstone bridge principle as a precise test of the QHARS self-consistency for dc measurements. Branched contacts and superconducting interconnections help to reduce ac and dc loading and leakage errors with near-zero resistance at magnetic flux densities of 9 T.**

Index Terms **— electrical measurement standards, quantized Hall resistance, epitaxial graphene, Wheatstone bridge.**

I. Introduction

Equivalent-circuit models of multi-terminal devices [1] have been employed to explore loading and contact resistance effects in measurements of R_H, the quantized Hall resistance (QHR). The main observation is that current drawn from the Hall voltage terminals can cause significant loading error due to the effective series source resistance $r_s = R_H/2$ between the contact (reservoir) and the edge state of the QHR device [2] in a strong magnetic field. In 1993, the metrological application of these principles was established by designs of circuits with multiple links between two or more devices [3]. The first link carries the majority of the current and sets up the equipotential edges on each device, so that Hall voltage interconnections have much smaller loading currents. Thus, loading and dc contact resistance effects can be reduced to negligible levels in QHARS networks. Likewise, multiple connections minimize the effects of parasitic loading in impedance measurements of single devices, and the development of QHR standards in the audio-frequency range has been based on this advance.

II. Ac measurement standards

Prior work in the metrology community with ac QHR standards [4], [5] has not incorporated QHARS devices, since complex circuit interconnections increase the parasitic capacitance. Positive contributions to the frequency-dependent impedance [4] may occur when capacitive current flows between the edge states and conductors that shield the device. Loss occurs only at the edges because the Corbino effect prevents dissipation from the interior, incompressible state of the two-dimensional electron gas. Similarly, ac current across the capacitive junction between the two equipotential edges creates a negative impedance contribution. We have recently reported on epitaxial graphene QHE devices with single-layer NbTiN superconducting interconnections [6], [7] and propose to use this technique for developing ac QHARS having 13 devices in parallel, yielding a resistance near 992.8 Ω. Confocal optical microscope images of sections of prototype arrays are shown in Fig. 1. Superconducting connections include branching contacts to the source and drain [7] and do not require isolated crossovers of the current and potential leads.

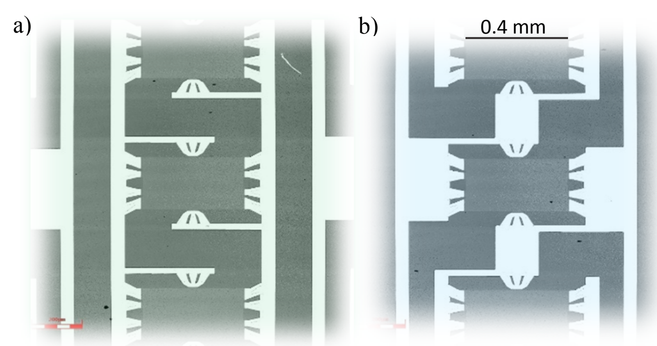

Fig. 1. QHARS device arrays. (a) Current flows in the same direction for all devices. (b) Current flows in alternating directions for adjacent devices to reduce capacitive losses between devices.

III. Dc measurement standards

In comparison with cryogenic current comparator (CCC) systems, room-temperature DCC bridges are less expensive and can be controlled through intuitive automated interfaces. Resistance standards at 1000 Ω are essential for DCC metrology based on the $\nu = 2$ plateau ($R_H \approx 12.9064$ kΩ) and for DCC scaling measurements between 100 Ω and 10 kΩ.

We previously reported on scaling results for DCC measurements based on a single device [7], finding Type A uncertainty about five times smaller for ratios of 1 kΩ/100 Ω than for 12.9 kΩ/1 kΩ with the same current of 1 mA applied to the 1 kΩ standard. Lower uncertainty results for a 1 kΩ/100 Ω ratio because the 1 kΩ measurement current flows in the more sensitive primary winding. Laboratories using DCC bridges could thus improve SI traceability by using QHARS devices at 1 kΩ as the realization of the unit.

Designs of some QHARS incorporate hundreds of devices at present [8] – [11], and superconducting connection designs may allow even higher density integration [6]. The concern that we address for wider adoption of QHARS technology at dc is the reliability of quantum SI traceability. Recommended longitudinal resistance and contact resistance measurements, used for single QHR devices, are impractical at large scales.

Figure 2 shows a dc QHARS circuit with superconducting interconnections. Two identical series-parallel (S/P) arms formed by sets of 11 and 15 QHR devices create a balanced Wheatstone bridge at two null points with voltage V_{SD} applied at the source and drain. A resistance of ≈1016.868 Ω is realized by the series-parallel arms. Three sets of 14 devices in series (S) between the source and drain trim the resistance correction to ≈ -14.696 μΩ/Ω from the nominal 1 kΩ value, and also have intermediate terminals. The design of the array allows an estimation of QHARS resistance error from the consistency of null-voltage measurements at the intermediate terminals with voltages of $V_{S/P} \approx 0.577\ V_{SD}$ and $V_S = 0.5\ V_{SD}$.

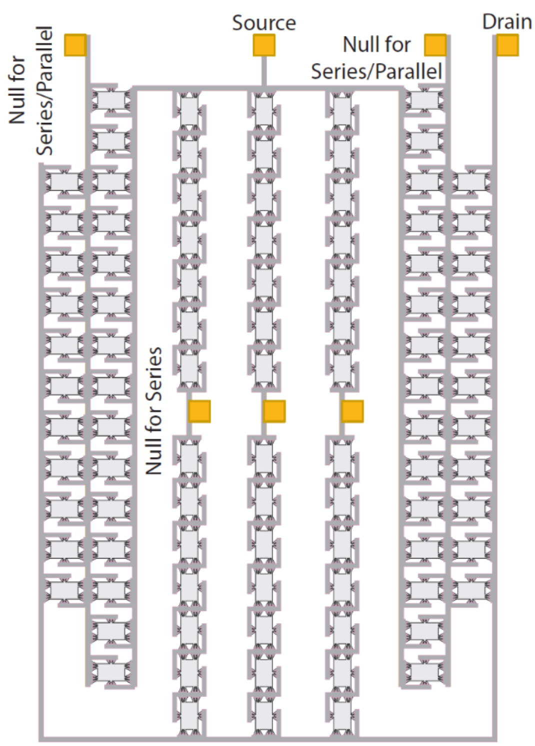

Fig. 2. QHARS array of 94 QHR devices with symmetric Wheatstone bridge elements allows null voltage measurements between intermediate contacts at similar voltage.

IV. Conclusion

Our approach condenses the multi-series interconnection principle by using superconducting NbTiN junctions to create two-terminal series and parallel quantum Hall arrays, thus eliminating possible errors from leakage and reducing internal loading errors in QHARS circuits. The capacitive parasitic loading error is minimized, since loading current is supplied by the source and drain, and this may allow parallel QHARS arrays to provide an alternative to single devices for use in ac bridges. To improve dc reliability, we will apply the Wheatstone bridge principle for *in-situ* characterization of QHARS circuits so that any contact resistance and longitudinal resistance contributions also may be detected for reduced uncertainty.

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