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INVESTIGATING THE USE OF MULTIMETERS TO MEASURE QUANTIZED HALL RESISTANCE STANDARDS*†

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Abstract

A new generation of digital multimeters was used to compare the ratios of the resistances of wire-wound reference resistors and quantized Hall resistances. The accuracies are better than 0.1 ppm for ratios as large as 4:1 if the multimeters are calibrated with a Josephson array.

Introduction

The integral quantized Hall resistance $R_H(i)$ of a two-dimensional electron gas [1] became the new world-wide resistance standard on 1 January 1990, where

$$R_H(i) = \frac{V_H(i)}{I} = \frac{R_K}{i}. \quad (1)$$

$V_H(i)$ is the Hall voltage of the ith resistance plateau, I is the current through the sample, and R_K is the von Klitzing constant, which has been assigned the value 25,812.807 Ω exactly [2].

The national standards laboratories require the highest possible accuracies for realizing the new representation of the ohm. They can achieve total one-standard-deviation uncertainties of 0.015-0.030 ppm using 1:1 potentiometric measurement systems [3,4] and Hamon resistance scaling networks [5], or 0.015-0.037 ppm using cryogenic current comparators [6,7].

In the future, other types of laboratories may find it desirable to have quantized Hall resistance (QHR) measurement systems rather than depend solely on standard resistor calibrations at the national standards laboratories and on measurement assurance programs (MAPS). Those laboratories will require accuracies of at least 0.1-0.2 ppm in order to compete with the MAPS method and justify the time and expense of building and maintaining a QHR system.

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Summary

We investigate here the feasibility of a simple QHR measurement system, namely the use of a digital multimeter to compare the dc voltage ratio of a QHR sample with that of a reference resistor connected in series with the sample. The multimeter would be calibrated with a Josephson array measurement system since an array would almost certainly be an integral part of any laboratory wanting an accurate QHR measurement system.

We tested the accuracy of this method by using two different Hewlett-Packard 3458A Multimeters[1] operated in the dc voltage mode to obtain the voltage ratios. The multimeters were designated as DVM1 and DVM2. They were calibrated with the NIST Josephson array voltage calibration system [8]. The voltage ratios obtained by this method were compared with those obtained from very accurate measurements using an automated QHR potentiometric comparator system [9].

A QHR measurement system would use a single 10–kΩ reference resistor. We wanted however to make an accurate assessment of this method by comparing it with results from an automated potentiometric comparator system. Therefore, we used six QHR reference resistors instead. Four of the resistors were constructed [3] to have nominal values within several ppm of the 6,453.20–Ω (i = 4) quantized Hall resistance plateau. They are designated $R_1(4)$, $R_2(4)$, $R_3(4)$, and $R_4(4)$. $R_1(4)$ and $R_2(4)$ are in individual temperature-regulated air-bath enclosures. $R_3(4)$ and $R_4(4)$ are in a separate air-bath enclosure and can be used individually or connected in series to form a 12,906.40–Ω (i = 2) resistor. The last two resistors were constructed to have nominal values within several ppm of the 12,906.40–Ω (i = 2) quantized Hall resistance plateau. They are designated $R_5(2)$, $R_6(2)$ and are in a separate air bath enclosure. They can also be used individually or connected in series to form a 25,812.80–Ω (i = 1) resistor. These six reference resistors can therefore be used to obtain 1:1, 2:1, and 4:1 resistance ratios. The air-bath enclosures have all been continuously controlled to within ±0.002 °C at a nominal temperature of 27.4 °C for at least two years. The drift rates of the six resistors relative to the quantized Hall resistances are all less than 0.15 ppm/year.

We used an automated quantized Hall resistance potentiometric measurement system [9] to accurately inter-

[1]Brand names are used only for purposes of identification. Such use implies neither endorsement by the National Institute of Standards and Technology nor assurance that the equipment is the best available.

compare 1:1 voltage ratios of combinations of these six reference resistors. A potentiometer canceled most of the voltage drops across the reference resistors. Voltage differences were obtained from a digital voltmeter which read the output of a Leeds and Northrup 9829 Linear Amplifier[1] detector. The total one-standard-deviation random or type A uncertainty was typically ±0.004 ppm for each resistor intercomparison. This uncertainty was achieved with a 25.5 μA current after 1.5 hours of measurement in one configuration and then another 1.5 hours with the resistors interchanged. There was a 15 s wait time and then a 60 s integration period after each current polarity reversal.

We replaced the Leeds and Northrup 9829 Linear Amplifier[1] detector, digital voltmeter, and the potentiometer parts of the automated measurement system with either DVM1 or DVM2 and then made direct readings of the total voltage drops across the QHR reference resistors. Surprisingly, the standard deviation of the DVM method results were only about twice as large as those using the Leeds and Northrup detector, and that particular detector is unusually quiet. One would have to count four times longer with the DVM method to obtain the same random uncertainty as the detector. This would take about 6 hours for each resistor configuration. Typically we counted between 4.5-5.5 hours. The results for the DVM and potentiometer methods were identical within the ±0.01 ppm experimental uncertainties. No DVM calibrations were necessary for the 1:1 ratios because the voltages were nominally equal.

We next verified that the HP 3458A Multimeters[1] could be used with quantum Hall samples by comparing the 6,453.2-Ω (i = 4) quantized Hall resistance of the GaAs/AlGaAs heterostructures sample that now maintains the U.S. ohm with the reference resistor $R_1(4)$. Again the DVM and potentiometric methods were in complete agreement, and the standard deviations of the DVM method were the same whether using the QHR sample or a resistor. Therefore, the digital multimeters do not appear to disturb the sample.

Finally, we measured various 2:1 and 4:1 resistance ratios by the DVM method using DVM1 and DVM2, and compared the results with those obtained from the appropriate combinations of 1:1 ratio measured by the potentiometer method. The largest discrepancies were for DVM1. The uncalibrated DVM1 results were too small by 0.11 ± 0.05 ppm and 0.19 ± 0.05 ppm for the 2:1 and the 4:1 ratios, respectively. They were too small by 0.00 ± 0.05 ppm and 0.07 ± 0.05 ppm when calibrated with the Josephson array. The uncalibrated DVM2 results were too large by 0.04 ± 0.07 ppm and 0.04 ± 0.08 ppm for the 2:1 and the 4:1 ratios, and the calibrated results were too large by 0.00 ± 0.07 ppm and 0.03 ± 0.08 ppm, respectively.

The calibration correction uncertainties result mainly from the inability to reverse the voltage polarity of the Josephson array exactly. Consequently the calibration data must be collected for one polarity at a time, within about a half hour time period to minimize voltage drifts. Therefore the calibration measurement time is much shorter than the QHR measurement time. This appears to be the fundamental limitation to the QHR method, but the method does appear to achieve an accuracy within 0.1 ppm.

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