Progress on the Quantized Hall Resistance Recommended Intrinsic/Derived Standards Practice

Presenter/Author

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Abstract

The quantized Hall resistance (QHR) standard requires characterization tests which determine if and how a particular QHR device should be used as an intrinsic standard. The initial characterization at a qualified QHR laboratory would provide the following: 1) Verification that the device resistance was approximately equal to that of other QHR devices under prescribed conditions; 2) Assurance that the QHR device meets recognized quality construction standards; 3) Determination of the effect of temperature in the range below 1.5 K; 4) Determination of the approximate magnetic flux density which must be applied to measure the QHR standard. The device could then be used as a standard in another laboratory, which would be expected to characterize the device using procedures which are given in the Recommended Intrinsic/Derived Standards Practice. Some of the laboratory procedures are described.

Introduction

When the QHR has been properly characterized, and is maintained in the required laboratory conditions, it provides a resistance standard with a base value R_K which is related to fundamental constants. These fundamental constants are Planck's constant ($h \cong 6.625 \times 10^{-34}$ kg m^2/s) and the electron charge ($e \cong 1.602 \times 10^{-19}$ coulomb).

In all QHR devices a very thin layer called a two-dimensional electron gas (2DEG) forms at low temperature. A strong magnetic field applied normal to this 2DEG sets up quantized (Landau) energy levels. Resistance plateaus can be seen in a plot of resistance versus magnetic flux density. These QHR plateaus or steps occur when the magnetic flux density is such that the 2DEG electrical carriers fill an integer number i of energy levels. The QHR values are $R_H(i)$, given by

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$$R_H(i) = R_K / i \qquad \text{(eqt. 1)}$$

An international metrological committee, the Comité Consultatif d'Électricité (CCE), recommended in 1988 that all laboratories adopt an internationally accepted value for the von Klitzing constant R_K beginning January 1, 1990. This recommended value for R_K which is

$$R_{K\text{-}90} = 25\ 812.807\ \Omega \qquad \text{(eqt. 2)}$$

was deduced from determinations of the SI ohm and comparisons to the QHR.

Equation 1 and the value $R_{K\text{-}90} = 25\ 812.807\ \Omega$ give the following values for $R_H(i)$:

$$R_H(1) = 25\ 812.807\ \Omega \qquad \text{(eqt. 3)}$$

$$R_H(2) = 12\ 906.403\ 5\ \Omega \qquad \text{(eqt. 4)}$$

$$R_H(3) = 8\ 604.269\ \Omega \qquad \text{(eqt. 5)}$$

$$R_H(4) = 6\ 453.201\ 75\ \Omega \qquad \text{(eqt. 6)}$$

and so on. To avoid any problem with devices that are unsuitable for use as QHR standards, national laboratories and international organizations have developed characterization tests for QHR devices. The characterization procedure has been summarized in a set of technical guidelines published for the CCE[1]. Following these guidelines, generally the $R_H(2)$ and $R_H(4)$ values and the associated steps are used for precision resistance calibrations.

Description of a QHR standard

In the GaAs/AlGaAs and similar QHR heterostructures, the Landau energy quantum number i is inversely proportional to the magnetic flux density B,

$$i = hn_s / eB \qquad \text{(eqt. 7)}$$

where n_s is the carrier density. Processing techniques can be used to achieve the desired carrier density. In 1989 a joint project to produce QHR devices was initiated by the Bureau International des Poids et Mesures (BIPM) and a European consortium of standards and research laboratories called EUROMET. Over 350 GaAs/($Al_{0.3}Ga_{0.7}$)As heterostructure devices were successfully produced. The specification for n_s that was defined for the BIPM-EUROMET devices (n_s between $3.5 \times 10^{15}\ m^{-2}$ and $5 \times 10^{15}\ m^{-2}$ at 4.2 K) places the i=2 plateau between 7.3 T and 10.4 T in applied magnetic flux density.

The QHR device is commonly used like a four-terminal resistance standard with the voltage (sense) terminals constrained so they do not draw or inject a current. A typical device is equipped with eight contacts, as shown in Fig. 1a. Two contacts located at the narrow ends of the device are the source and drain which carry the measurement current (I_{SD}). Voltage contacts are arranged at intervals along both sides of the device. The contacts are separate and distinct, so current must flow through the 2DEG to pass from any one contact to another.

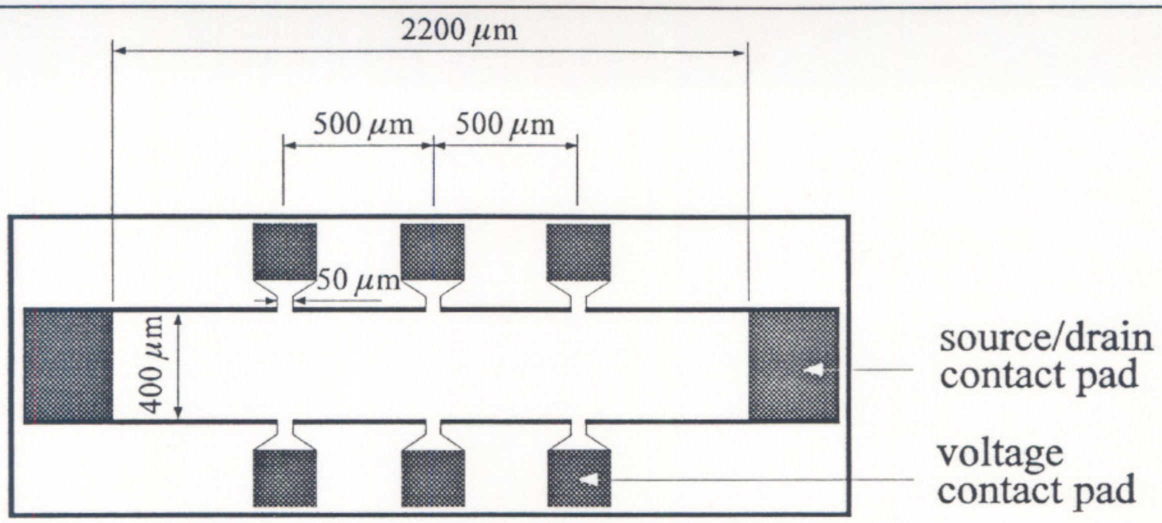

Fig. 1a. Example of a QHR heterostructure device layout

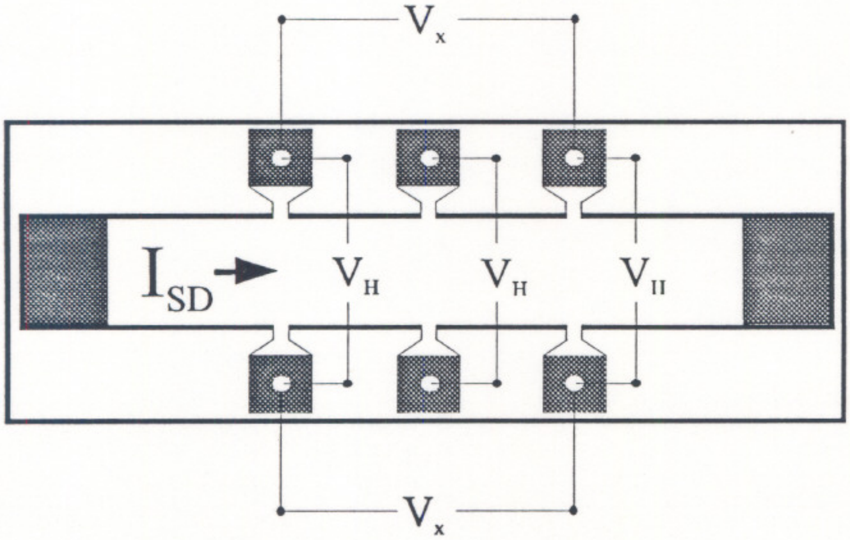

Fig. 1b. Several sets of voltages V_x and V_{II} at the contact pads

Because the QHR standard has distinct current and voltage contacts, a large two-terminal resistance may exist between any two measurement terminals. The Hall voltage (V_H) is measured at the voltage contact pairs at equal distance from the source and drain; one of each pair is on each side of the device (see Fig. 1b.). The Hall resistance (R_H) is equal to the voltage V_H (measured at any pair) divided by the measurement current I_{SD}. A longitudinal voltage (V_x) can be observed between any two voltage contacts along one side of the device while passing a current

I_{SD} through the source-drain. Longitudinal resistance (R_x) is defined to be this voltage V_x divided by I_{SD}.

A set of four resistance measurements constitute a complete measurement of the QHR standard. Two Hall voltage contact pairs are selected. These four contacts are at the corners of a rectangular area of the 2DEG; the measurements define the resistances around the sides of the rectangle. The value of the QHR standard is then taken to be the mean of the two R_H measurements, and the longitudinal resistance is taken to be the mean of the R_x measurements. The most accurate measurements of the QHR standard will be achieved for a given I_{SD} if the longitudinal resistance is zero, or has a very small minimum value.

General characterization requirements

The longitudinal resistance for the i=2 or i=4 plateau is usually near zero for some range of magnetic flux density near the plateau center. However, each QHR device has individual characteristics. Characterization of the device refers to measurement of the response to magnetic flux, current, and temperature; each of these parameters has important effects on the device. Characterization tests are also necessary to verify that the device contacts are in a condition that allows accurate measurements of the QHR standard.

A general characterization should be performed at a national laboratory or similar facility which can determine the suitability of the device as a standard, including temperature dependence and current dependence of the QHR value. It is recommended in the CCE guidelines that the supplier or user of the QHR device determine the minimum longitudinal resistivity for each plateau at various temperatures at least once. This temperature dependence may be different for different values of I_{SD}.

Measurements at device temperatures of 1.5 K to 4.2 K or above may be used to characterize R_H and R_x as a function of temperature. A repeatable constant of proportionality (relating V_H to V_x) for each set of Hall probes can be determined for most QHR devices. The CCE guidelines suggest that R_H measurements at temperatures below 1.5 K can then be corrected for small shifts due to temperature using the proportionality constant and the value of R_x obtained in the calibration laboratory. The laboratory that initially selects and characterizes a sample for use as a QHR standard should be able to provide support in determining the temperature correction procedure for QHR standards.

The general characterization should verify that the device contacts are suitable for QHR measurements. Each device contact consists of a metallic region on the top surface of the device and a conducting region below the surface reaching as far as the 2DEG layer. An incomplete conducting path within the device or poor bonding of wires or metallic pads on the device surface can cause high contact resistance. Device contact resistance should be measured for each I_{SD} and B (magnetic flux density) polarity.

The baseline plateau range of both the i=2 and i=4 plateaus should be determined at one or more temperatures and I_{SD}. The maximum deviation at the edges of the plateau from the ideal R_x value of zero must be defined to specify this width. General characterization also should determine the baseline value of B at the plateau center. Typical devices have a carrier density which changes by no more than two or three percent from one cool-down to the next.

Measurement characterization in the user laboratory

Laboratory requirements

Characterization test instruments should be carefully selected since electrical noise can damage a QHR device. It is best to connect test equipment with the instrument turned on, and with the measurement scale correctly set or with the output voltage at zero, and to disconnect test leads after tests are completed.

Constant current and lead resistance measurements

Constant current measurements are recommended before and after the QHR device is chilled. These measurements check the continuity of the device leads and contacts and show that the resistance along the device is generally uniform from source to drain. A constant current I_{SD} from a floating battery-operated current source is applied through the source and drain current leads. The voltage (sense) terminals are used to measure the voltage along the device from source to drain, and then the current is reversed and the measurements are repeated. The current I_{SD} is measured at an auxillary resistor. Typical lead resistance is measured through two leads, using duplicate sets of leads which are installed for the source and drain.

Magnetic flux density dependence characterization

Each QHR plateau is usable as a standard for some range of magnetic flux density. The plateau width can change by a few percent from one cool-down to the next. Higher temperature and measurement current reduce the plateau width. The QHR device must experience a magnetic flux density B that is relatively homogeneous. A flux density which is not sufficiently homogeneous can cause the plateau width to be much less than expected.

The magnetic flux density can be monitored using a magnetometer sensor mounted in the fringe field of the magnet. This flux density is proportional to the flux density at the device if the positions of the device and sensor are fixed and if no magnetic materials are near the sensor. Although the sensor should not have hysteretic behavior it is best to sweep the magnet current in a preferred direction (i.e., increasing current) each time the flux density is set. The flux density can also be calculated from the magnet solenoid current, with voltage and resistance corrections for the magnet leads and protection circuitry, if the solenoid current is always set by sweeping in a preferred direction.

Magnetic field direction dependence of the QHR

QHR calibrations can be made with either polarity of magnet current. The Hall voltage for a constant polarity source-drain current will reverse when the direction of the magnetic field is reversed. Therefore the Hall terminals which are at nearly the same voltage as the drain for one field direction will be close to the voltage of the source for the reversed field. Some characterization tests are affected by the direction of the magnetic field so this polarity should be recorded.

Contact resistance characterization

A two-terminal measurement between any two voltage terminals should show that a resistance of approximately R_K/i is measured when the QHR standard is used. This is the resistance of the 2DEG in series with the contact and lead resistances. The CCE guideline recommends that a battery-operated ohmmeter should be used for these two-terminal measurements to check the resistance of the contacts. The output current of the ohmmeter should not be greater than the usual measurement current I_{SD}.

Moderate contact resistance (below 1 kΩ) at the voltage contacts usually does not affect the longitudinal resistance or Hall resistance. Clear evidence of excess noise or diode-like resistance at low current is cause to avoid the use of a particular voltage contact for QHR measurements. If excess voltage noise is observed at any contact or a contact is significantly more resistive than others, noise voltage measurements should be made to verify the contact quality. Noise across a terminal pair should be less than that observed across a room temperature resistor with the same value. In some cases, especially when the device has been accidentally exposed to large currents, excess noise may be removed by warming the device to room temperature.

Longitudinal resistance characterization measurements

The longitudinal resistance V_x / I_{SD} should be measured at three closely spaced magnetic flux density values near the center of each QHR plateau used for calibrations. The measurements should show that R_x is less than a small fixed value which is safe for that particular device. A setting of the magnetic flux density (B_{avg}) close to the average of these three magnetic flux settings should then be used throughout the calibration measurements at that plateau.

The longitudinal resistance characterization at B_{avg} should accurately determine the residual longitudinal resistance on both sides of the device. The most sensitive measurements can be made between voltage contacts with the largest separation on the device. If the resistance minimum value is found to be greater than acceptable, or if the width of the minimum is narrower than 2% of the magnetic flux value at the plateau, the current I_{SD} may be too high at the device temperature maintained. If a slope in the longitudinal resistance is observed in the central region, one can shift the central B_{avg} by 2% or 3% and repeat the measurements. Accurate measurements to determine the minimum value of R_x also allow R_H measurements to be corrected for small shifts due to temperature. Each plateau that is used for calibrations must be characterized, and the same I_{SD} should be used in calibrations.

Interpreting the characterization measurements

Characterization should determine if temperature cycling has had any destructive effect on the device and verify that the device is useable as a QHR standard. Characterization of the contact resistance and residual longitudinal resistance is necessary for any QHR device used in calibrations. These two sets of measurements should be made before any calibrations, and usually are repeated each day that calibrations are made.

The CCE guidelines estimate that a temperature correction of up to 3 parts in 10^8 can be used with negligible effect on the accuracy of the measurement. This allows some flexibility in the temperature of the device. The BIPM-EUROMET devices can be used up to a temperature of at least 1.5 K, and some other devices have similar temperature characteristics. A standard uncertainty related to the device characteristics should be in the range of one part in 10^8 up to 5 parts in 10^8 of the measurement value if the device meets the characterization requirements and has been corrected for temperature dependence at the base temperature used. The user might assign a standard uncertainty based on the accuracy of longitudinal resistance measurements, the frequency of the characterization measurements, and the repeatability of characterization results.

Footnote

[1] Delahaye, F., "Technical guidelines for reliable measurements of the quantized Hall resistance," *Metrologia*, vol. 26, pp. 63-68, 1989.