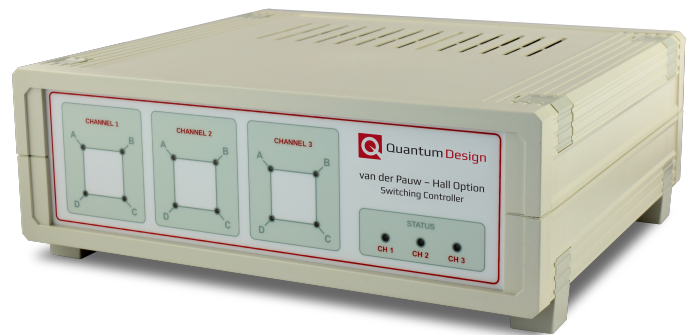# van der Pauw - Hall Option

# User's Manual



## Quantum Design

# Additional Resources

This user manual has been compiled as a comprehensive reference to explain the theory, operation, and maintenance of your Quantum Design instrumentation. Additional materials related to this product may also be available on Pharos (Quantum Design's online repository for users) including representative data sets, example sequences, software utilities, etc. Video demonstrations and tutorials are available on Quantum Design's YouTube channel, and further documentation describing solutions to commonly encountered challenges in data collection and interpretation can be found in various Application Notes in the Applications section of the QDUSA website.

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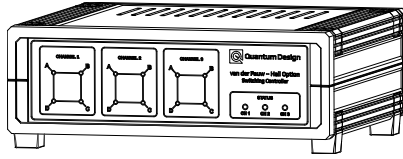
QD China

QD Europe

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QD Taiwan

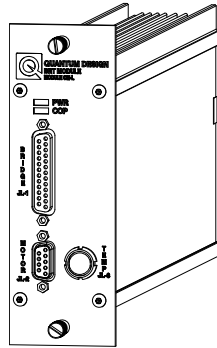QD UK & Ireland

Domo-Technica Australia
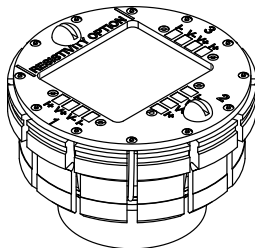
# Key Components

**Automatic Switching Box**

Permutes the routing of sample contacts to the measurement electronics.

**BRT Module (Not Included)**

Supplies the excitation current and detects the sample voltage response.

**Resistivity Puck (Not Included)**

Used for sample mounting; facilitates electrical interfacing between the sample and measurement hardware.

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# Overview of the vdP-Hall Option

## 1.1 What the Option Measures

The van der Pauw-Hall option leverages the electronics of the BRT module in coordination with switching electronics to perform resistance measurements in a variety of different configurations. By permuting the particular spatial arrangement of the leads which source current and detect the resulting voltage, and averaging these results, the accuracy of the reported resistance can be improved using the van der Pauw technique.

A similar scheme is employed in the presence of a magnetic field applied normal to the plane of the sample to extract the Hall coefficient. Here, the careful choice of permutations avoids the need to change the direction of the field, a time-consuming operation for the superconducting solenoids responsible for producing these fields, in the PPMS family of instruments.

## 1.2 Measuring Resistance

### 1.2.1 The Four-Probe Configuration

The first transport measurement most individuals will encounter is a basic two-probe measurement with a hand-held (and likely digital) multimeter. While this tool is invaluable for quick resistance checks around the lab, its limitations are readily apparent upon examining the circuit diagram more carefully. By using the same conductor for both the excitation (typically current) and response detection (typically voltage) on either side of the element in question, the reported result is not necessarily derived exclusively from the sample response.
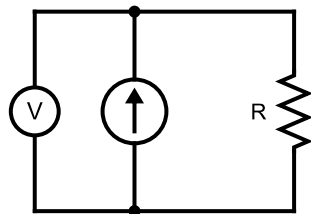


**Figure 1-1:** Basic representation of a resistance measurement of the resistor R using a current source and voltmeter in the two-probe configuration.

Instead, the voltage measurement includes not only the potential drop across the sample, but also those across the wires and any potential contact resistance, as seen in Figure 1-2:

**Figure 1-2:** The same two-probe measurement, here with lead and contact resistances depicted explicitly.
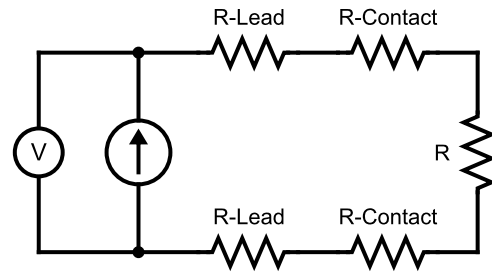
For samples where the resistance of interest is comparable to, or smaller than, the contact and lead resistances, this can represent a significant challenge to acquiring an accurate result. A more sophisticated wiring configuration designed to mitigate this effect is sometimes termed "Kelvin sensing" but more commonly referred to as a "four-probe" measurement.
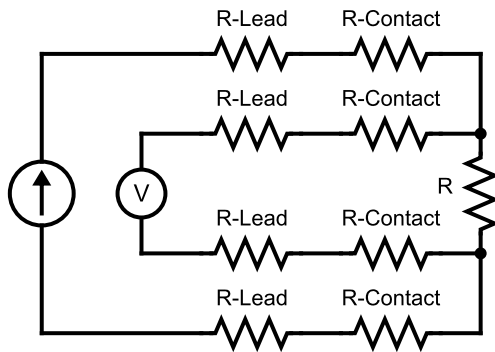


**Figure 1-3:** The four-probe lead configuration, again shown with explicit lead and contact resistances.

For the configuration shown in Figure 1-3 a sufficiently ideal (i.e.: high impedance) voltmeter should have negligible current flowing through the sensing leads, so any potential drop registered can be attributed only to the sample element itself. In many cases, this allows far smaller resistances to be measured accurately, and removes the need to be overly concerned with the details of lead material choice or the method of making lead-to-sample contact.

## 1.2.2 Inferring Resistivity

While the four-probe method provides a thoughtful technique to accurately determine the measured *resistance*, the quantity more typically of principal interest is its intrinsic analog, *resistivity*. These properties are of course related to one another by the familiar relation,

$$\rho = \frac{A}{L} \cdot R$$

...where $A$ represents the constant cross-sectional area through which a uniform current of density $j = I/A$ is assumed to flow between two voltage leads a distance $L$ apart.

This expression is sometimes applied with limited consideration for the assumptions which come along with it. As a result, samples having either poorly defined geometric cross-sections, ambiguous voltage lead spacings from large or irregular contacts, non-uniform bulk current densities, or any combination of these, can cause inaccuracies in the derived *resistivity* value in spite of an accurate resistance measurement. For illustrating general trends in a series of samples these systematic errors are often not large enough to cause problems, but when the accuracy of a resistivity measurement is critical, it can be helpful to consider alternate techniques.

## 1.2.3  The van der Pauw Technique

The method originally reported by Leo J. van der Pauw[1] presents a solution to the general problem of four-probe electronic transport in uniformly flat samples of arbitrary shape. The power of this technique lies largely in removing the need for imprecise measurements of the planar geometric factors since it constitutes a direct measure of the sheet resistance. Determining the resistivity still requires prior knowledge of the sample *thickness*, but for samples meeting the criteria for a van der Pauw measurement it is more common to have determined this by a separate technique.

### 1.2.3.1 Criteria for Application

Several assumptions must be valid for the application of the van der Pauw relation to be valid for a given sample. They are summarized here as follows:

- Contacts to the sample lie at the outer boundary

- Contact areas are small[1] compared to the total area of the sample

- The sample is of uniform thickness, which itself is small in comparison to the areal dimensions

- The sample surface is 'singly connected', that is- the sample has no holes

Beyond these conditions, the sample boundary can take any arbitrary shape, and the leads placed at any point around it, an example of which is shown in Figure 1-4. In practice, certain special shapes (so-called 'cloverleaf' and 'Greek cross' patterns, for instance) provide their own particular advantages in minimizing errors arising from finite lead size; these various options are treated in further detail in literature.
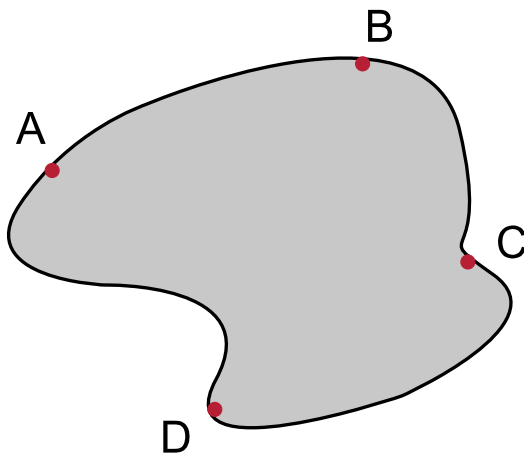


**Figure 1-4:** Diagram of an arbitrarily-shaped sample with labeled contacts for a hypothetical van der Pauw measurement.

### 1.2.3.2 The van der Pauw Relation

The principal result of van der Pauw's work is summarized in the following relation:

$$\frac{\rho}{t} = \frac{\pi}{\ln(2)} \frac{V_{AB,CD} + V_{BC,DA}}{2I} f\left(\frac{V_{AB,CD}}{V_{BC,AD}}\right)$$

This equation relates three distinct quantities:

---

[1] L. J. van der Pauw, *A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Shape*, Philips Research Reports, Vol. 13 (1958).

[1] Technically, the derivation assumes infinitesimally small contacts, though in practice errors from finite-size contacts are not prohibitively large at the approximate scales depicted in the figures shown here.

a. $\frac{\rho}{t}$ - the sheet resistance

b. $V_{\mathrm{AB,CD}}$ - the voltage drop measured between points C and D, $V_D - V_C$, while sourcing $I$ amps of nominally 'positive' current from A to B

c. $V_{\mathrm{BC,DA}}$ - the voltage drop measured between points D and A, $V_A - V_D$, while sourcing $I$ amps of nominally 'positive' current from B to C

The function $f$ takes a value which satisfies the following expression:

$$\frac{V_{\mathrm{AB,CD}} - V_{\mathrm{BC,DA}}}{V_{\mathrm{AB,CD}} + V_{\mathrm{BC,DA}}} = f \cdot \mathrm{acos}\left(\frac{\exp(\ln(2)/f)}{2}\right)$$

A few notes to make about the van der Pauw relation: the fundamental quantity that is calculated from the voltage measurements is the sheet resistivity, notated as $R_S$. This quantity is clearly related to the bulk resistivity by the sample thickness and is further described in Section 1.2.4.1. The second important feature is the geometric relationship between the two voltage measurements required to evaluate it. These are reproduced below in Figure 1-5 for the arbitrary sample used earlier.



Configuration 1                    Configuration 3
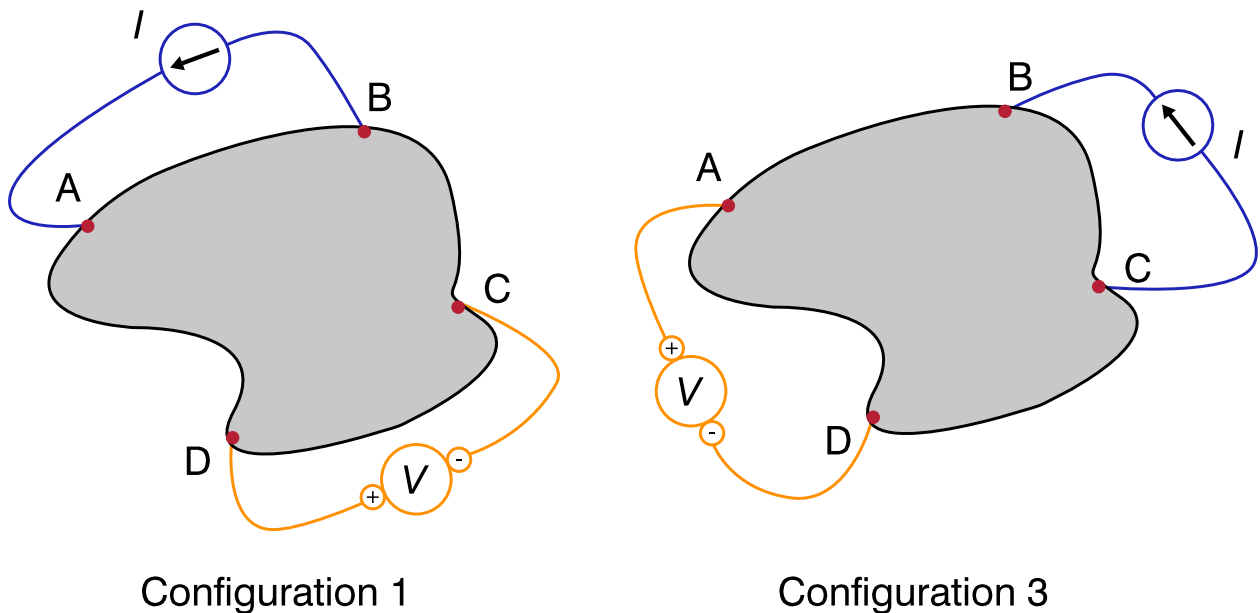
**Figure 1-5:** Two possible lead configurations, corresponding to notation used in the prior expression of the van der Pauw relation. Note the polarities of both the current source and voltage measurement hardware are denoted explicitly.

With these two configurations depicted graphically, here the relationship between them is defined as a '90 degree rotation' of the contacts. Examining Figure 1-5 shows that moving from 'Configuration 1' to 'Configuration 3' constitutes an incremental, clockwise, 'rotation' of the leads by a single position; put another way: whatever was connected to A moves to B, B's connection moves to C, C's connection moves to D, and finally D's connection moves to A.

A moment here is taken to simplify both the notation and the schematic representation of these wiring configurations. Though it should remain understood that all of the subsequent analysis still applies to a sample of arbitrary shape, such as the one depicted above, in the interest of simplicity this explicit representation is abandoned in favor of a basic square geometry. The notation is also adjusted such that $V_{\mathrm{AB,CD}}$ will simply be labeled as $V_1$, and $V_{\mathrm{BC,DA}}$ as $V_3$.
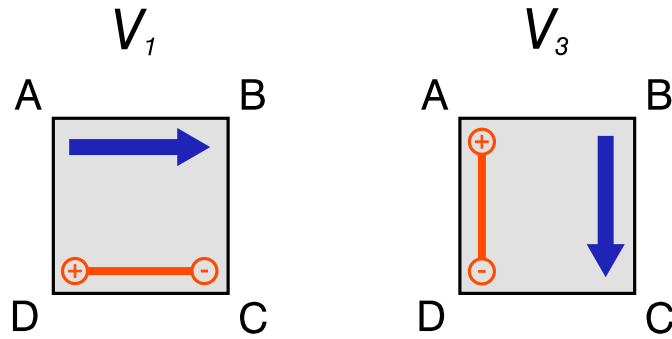
**Figure 1-6:** Alternative schematic representation and label notation for two lead configurations of a van der Pauw measurement. This diagram contains the identical information as Figure 1-5, only with the simplified scheme. The blue arrows refer to the direction of current flow in the sample, while the orange symbol indicates the polarity of the voltage measurement associated with the label $V_n$.

### 1.2.3.3 Further Improvements to the Method

A common problem in DC measurements is the unavoidable presence of static DC offset signals. One conventional method to remove these is to execute the voltage measurement twice, but the second time the source current's polarity is reversed. It follows that the component of the total voltage corresponding to the sample should also change sign, but the static offset will not.

Assigning the labels $V_1$ and $V_2$ to these respective measurements, the results can be represented as

$$V_1 = V_{\text{samp}} + V_{\text{offset}}$$

$$V_2 = -V_{\text{samp}} + V_{\text{offset}}$$

...and so a linear combination yields:

$$V_{\text{samp}} = \frac{V_1 - V_2}{2}$$

Such analysis can be applied to the two independent measurements depicted in the prior section to produce a more sophisticated implementation of the van der Pauw measurement of resistivity:

$$\frac{\rho}{t} = \frac{\pi}{\ln(2)} \frac{1}{2I} \left( \frac{V_1 - V_2}{2} + \frac{V_3 - V_4}{2} \right) f \left( \frac{V_1 - V_2}{V_3 - V_4} \right)$$

Now there are four unique voltages that must be quantified to evaluate the expression, but the result should be robust against the presence of any static DC offset voltages which would otherwise skew the reported value. For completeness the lead configurations are depicted in Figure 1-7.

**Figure 1-7:** Four unique lead configurations constituting an application of the van der Pauw technique which aims to eliminate the influence of static DC offsets from the result.
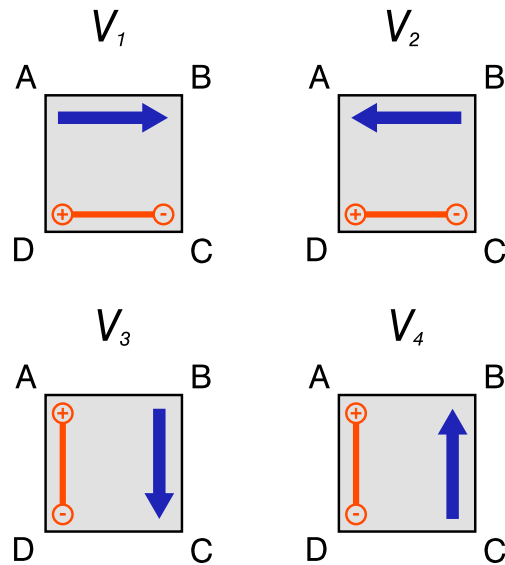
For this method then, a 'complete' van der Pauw sheet resistance measurement can be though of as comprising a nominal lead configuration ($V_1$), that configuration 'rotated' by 90 degrees ($V_3$), and the associated polarity-swapped versions of both orientations ($V_2$ and $V_4$, respectively). Due to the reciprocity of electrical networks of passive elements, there exists a second set of these measurements which must return the same result. These can be derived simply by 'rotating' each of the above voltages by 180 degrees, to produce configurations $V_5$ through $V_8$, as shown in Figure 1-8. These alternate configurations are governed by an analogous expression of the van der Pauw relation:

$$\frac{\rho}{t} = \frac{\pi}{\ln(2)} \frac{1}{2I} \left( \frac{V_5 - V_6}{2} + \frac{V_7 - V_4}{2} \right) f \left( \frac{V_5 - V_5}{V_7 - V_8} \right)$$

These two independent measures of the sheet resistivity $R_S$ should yield the same answer to within the experimental uncertainty of the measurement $\delta R_S$. If the two were averaged:

$$R_S^{\text{avg.}} = \frac{R_S^{V_1 \ldots V_4} + R_S^{V_5 \ldots V_8}}{2}$$

...then the resulting uncertainty simply adds in quadrature while being scaled by the factor $\frac{1}{2}$:

$$\delta R_S^{\text{avg.}} = \frac{\sqrt{(\delta R_S)^2 + (\delta R_S)^2}}{2} = \frac{\delta R_S}{\sqrt{2}}$$

By quantifying the eight unique voltages from each configuration and averaging the two independent measures of the sheet resistance, the uncertainty can be reduced by a factor of 1.414..., thereby increasing the confidence in the reported result.
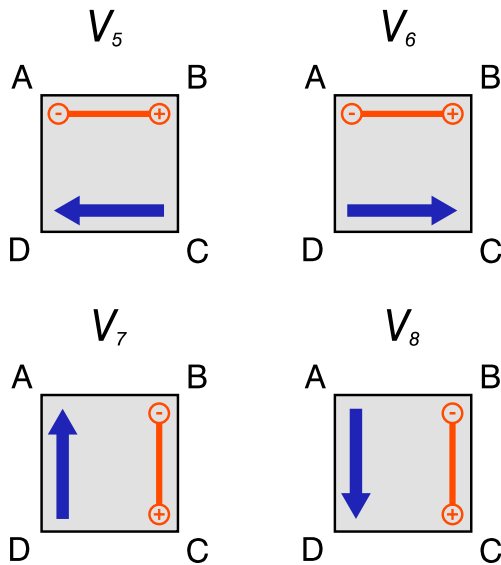
**Figure 1-8:** The four unique *reciprocal* lead configurations constituting an application of the van der Pauw technique aiming to eliminate the influence of static DC offsets from the result.

Reiterating a point from earlier: if the thickness $t$ of the sample is known, taking its product with the final value of sheet resistance yields the intensive property of the sample's bulk resistivity:

$$\rho = t\,R_S$$

## 1.2.4 Reported Units

**Table 1-1:** Units of reported van der Pauw resistivity properties.

| Property Name | Units | Description |
|---|---|---|
| $I$ | $[\mu\text{A}]$ | Excitation Current |
| $\rho$ | $[\Omega] \cdot [\text{cm}]$ | Resistivity |
| $R_S$ | $[\Omega]/\square$ | Sheet Resistance (see Section 1.2.4.1) |

Note that the units of the reported quantities are also always indicated by the column titles within header of the `.dat` file as well.

### 1.2.4.1 Sheet Resistance

The reported units of the sheet resistance merit additional explanation to ensure proper interpretation. Beginning with the common expression relating bulk resistivity to 'volume' resistance $R$ and applying dimensional analysis using SI units:

$$\rho = R\frac{A}{L} = R\frac{W\,t}{L} = [\Omega]\frac{[\text{m}]\,[\text{m}]}{[\text{m}]}$$

Since two of the length *dimensions* cancel, resistivity ends up with units of $[\Omega]\,[\text{m}]$. Repeating the exercise for the sheet resistance:

$$R_S = \rho/t = R\frac{W\,t}{L}\,\frac{1}{t} = R\frac{W}{L} = [\Omega]\frac{[\text{m}]}{[\text{m}]}$$

Notice from the way both the bulk resistivity and the sheet resistance are defined, the two values for thickness are identical and necessarily cancel, such that from a dimensional standpoint this simplifies down to merely units of $[\Omega]$

. In the special case where $L = W$ (a square-shaped sample of uniform thickness) the sheet resistance and volume resistance are identical: $R_S = R$, but in general this is not true.

To differentiate the units between these similar but distinct quantities, the sheet resistance is often reported as 'ohms per square', typically denoted as $\Omega/\square$. This helps to remove some ambiguity, but it should remain understood that this is a convention of notation, and the $\square$ just represents the dimensional *unit* ratio of $[\mathrm{m}]/[\mathrm{m}]$.

### 1.2.4.2 Converting to SI

Notwithstanding the notational embellishment of 'ohms per square' discussed just prior, the units for reported quantities of van der Pauw resistivity are standard SI, readily converted to base units using the standard metric prefixes.

# 1.3   Measuring the Hall Coefficient

As will be shown, the ability to arbitrarily permute the contacts on a sample has utility not only to measure the sample's longitudinal resistivity, but also another important transport property: the Hall coefficient. This value quantifies the extent to which a sample exhibits a transverse voltage potential developing orthogonal both to the direction of the sourced current and an applied magnetic field, termed the Hall effect.

Alongside a material's resistivity, the Hall coefficient is a key component in determining the mobility of the charge carriers, so its often of just as much interest to the researcher.

## 1.3.1   Applying the Drude Model

For an idealized bar-shaped sample with uniform current density, the spatial relationship between the current leads, the electric field created in the sample, and the corresponding lines of equipotential can be visualized as shown in (a) of Figure 1-9. Borrowing from the Drude model[2], the equation of motion for the time averaged behavior of the charge carriers for this case is given as:

$$\left\langle \vec{F}_{\mathrm{Net}} \right\rangle = q \cdot \vec{E} - \frac{m}{\tau} \langle \vec{v} \rangle$$

...where the carrier charge is given by $q$, its mass as $m$, and velocity by $\vec{v}$; angled brackets represent the time average over all carriers. The symbol $\tau$ corresponds to the average time between a scattering event experienced by a charger carrier. In the steady state, where there is no average net force on the carriers, this reduces to:

$$q \cdot \vec{E} = \frac{m}{\tau} \langle \vec{v} \rangle$$

With current density is defined as $\vec{j} = q\, n\, \vec{v}$, for a carrier density $n$,

$$q \cdot \vec{E} = \frac{m}{\tau\, n\, q} \cdot \left\langle \vec{j} \right\rangle$$

Collecting the constants together yields the quantity typically referred to as resistivity, $\rho = m/nq^2\tau$, and the expression takes the form of the 'microscopic' version of Ohm's Law:

$$\vec{E} = \rho \left\langle \vec{j} \right\rangle$$

---

[2] This derivation largely follows the standard one appearing in texts such as *Introduction to Solid State Physics* (C. Kittel), or *Solid State Physics* (N. Ashcroft, N. Mermin). A similar discussion is available online from the Delft University of Technology.

Despite its familiarity, this remains a noteworthy result: in order to maintain a *constant velocity* of the conducted electrons, they must be *constantly accelerated* by the applied electric field in order to balance the 'drag' force introduced by the Drude model which approximates the electron-nuclei scattering events in metallic solids.



(a)                                              (b)
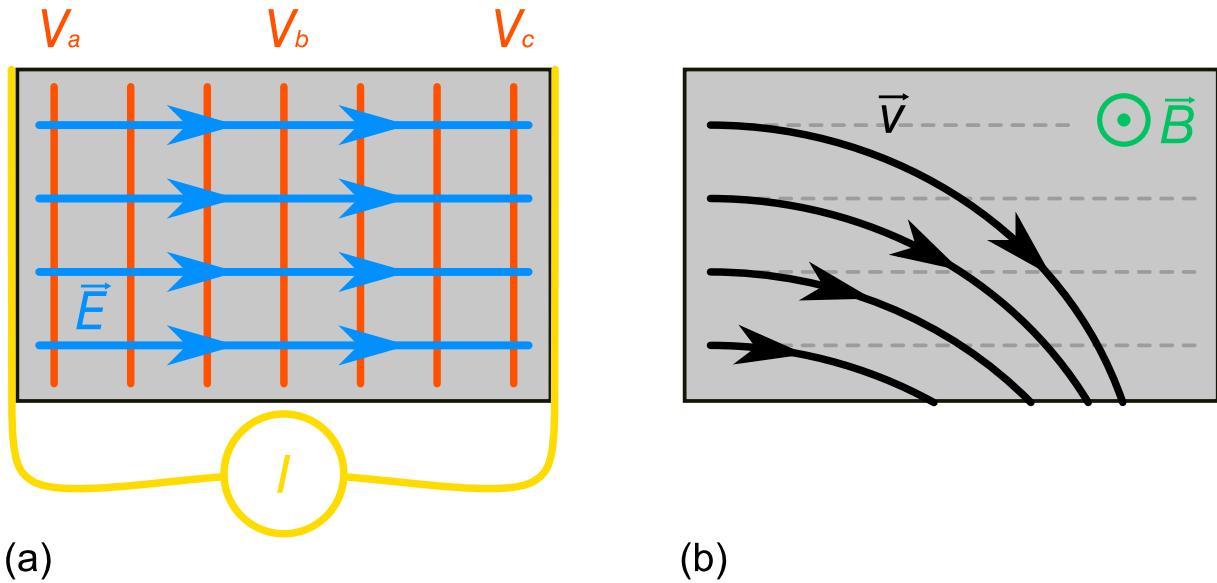
**Figure 1-9:** (a) Spatial relation between the current flow, electric field, and related lines of equipotential in a bar-shaped sample. (b) Trajectory paths of charge carriers with constant velocity in a uniform magnetic field.

If a uniform magnetic field is applied perpendicular to the plane of Figure 1-9 the more generalized equation of motion is found by including the complete form of the Lorentz force to give:

$$\left\langle \vec{F}_{\text{Net}} \right\rangle = q \cdot \left[ \vec{E} + \left( \langle \vec{v} \rangle \times \vec{B} \right) \right] - \frac{m}{\tau} \langle \vec{v} \rangle$$

The presence of the magnetic field creates a downward (upward) force on the positive (negative) charge carriers flowing through the sample, altering their trajectories as approximately shown in (b) of Figure 1-9

The electric field arising from this build-up of static charge, shown in Figure 1-10, eventually becomes large enough to balance the deflection force and the steady state is achieved. The same constant current density $\vec{j}$ again flows longitudinally across the sample again, but now there is a transverse electric field present as well. The associated electric potential is referred to as the 'Hall voltage' and, as will be shown, provides critical insight to the conduction properties of a material.

**Figure 1-10:** The transverse electric field and corresponding Hall potential associated with the build-up of charge carriers at the sample boundary arising from the presence of a uniform out-of-plane magnetic field as shown in Figure 1-9 (b).
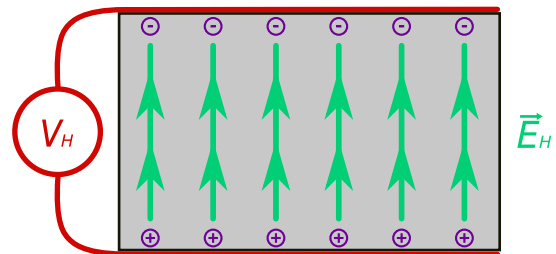


Next, evaluating then the equations of motion for the steady-state,

$$q\,\vec{E} = \frac{m}{\tau} \langle \vec{v} \rangle - q \left( \langle \vec{v} \rangle \times \vec{B} \right)$$

...and substituting in the expression for the current density in this more general case gives:

$$\vec{E} = \frac{m}{n\,q^2\tau}\left\langle \vec{j} \right\rangle - \frac{1}{n\,q}\left\langle \vec{j} \right\rangle \times \vec{B}$$

Dropping the notation of the time-average brackets (but not the meaning they imply) for the sake of simplicity and separating the vectors' magnitudes from their directional unit vectors yields

$$\vec{E} = \frac{m}{n\,q^2\tau}j\ \hat{j} - \frac{B}{n\,q}\ j\ \hat{j} \times \hat{B}$$

Here, the first term is identical to the results from the zero-field case: the magnitude of the electric field required to move a constant current density $j$ through the sample is set by the proportionality constant of the resistivity $\rho$. The

second term provides the magnitude of the electric field required to *balance the deflection force* in order to achieve a steady-state; as expected, the sign indicates it points opposite the magnetic-field-derived component of the Lorentz force. This component is associated with the measured Hall voltage, and is notated as such:

$$E_{\mathrm{H}} = -\frac{j\,B}{n\,q}$$

From this simple form, we see that the Hall component of the electric field is linearly proportional to the current density and the applied magnetic field, two values that can be controlled experimentally. The remaining constant, $-1/nq$, is termed the 'Hall coefficient' and typically notated as:

$$R_H = -\frac{1}{n\,q}$$

The denominator contains two terms of great interest: the sample's charge carrier density and the explicit charge of the carriers.[3] The latter is particularly important, since it provides a clear test for discerning the polarity of charge carriers in a material. Measurements of the Hall potential provided the first experimental evidence that negative charges were in fact the dominant carriers in most metals, years before the existence of electrons had been confirmed.

## 1.3.2 Application to Laboratory Measurements

For a basic application of these expressions to extract meaningful information from a sample, consider the same bar-shaped sample used thus far in this section. A constant current $I$ is sourced through the sample, with two separate voltage measurements- $V$ and $V_{\mathrm{H}}$ -carried out. Figure 1-11
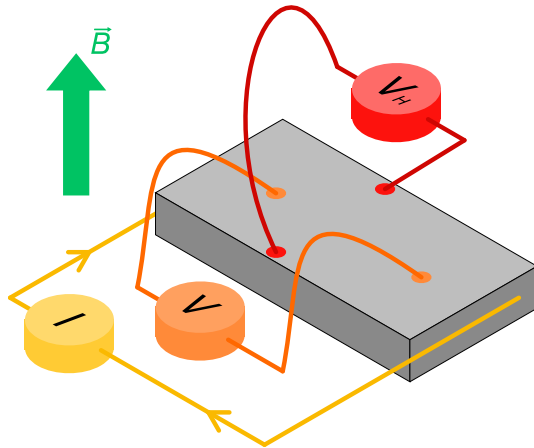


**Figure 1-11:** Lead configuration for a measurement of both the longitudinal and transverse potential drops across a sample subject to a uniform current and constant applied magnetic field.

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[3] More sophisticated analysis is required in the case of multi-carrier systems at modest magnetic fields. This topic is not treated here, and all carrier concentrations reported by the software assume a single-carrier system.

The underlying issue concerns how the laboratory-measured electric potential relates to the more fundamental electric field, which is itself proportional to the material properties of interest. Recall that the electric potential between two points amounts to a contour integral between those points:

$$V = -\int_C \vec{E} \cdot d\vec{l}$$

For a perfect alignment of the voltage contacts with the respective electric fields the experimenter wishes to probe these integrations become trivial: $V = d_1\,E$, and $V_H = d_2\,E_H$, where the lengths are as depicted in (a) of Figure 1-12

If the leads are misaligned, how does this impact the measurement? Figure 1-12 (b) depicts a static rotation of the contacts of 10 degrees. Now the measured voltage results from a contour integral along a path which is no longer in the trivial basis of the direction of current flow $(\hat{j})$ and the axis normal to it. Fortunately, the electric field is a conservative vector field, and owing to the gradient theorem it turns out the result of the integration is independent of the particular choice of path. With this freedom, a path can be chosen as the other legs of the right triangle, along which the electric field is a constant. As a result, the measured voltages will now give:

$$V' = d_1\,[E\cos(\theta) + E_H\sin(\theta)]$$

$$V'_H = d_2\,[E\sin(\theta) + E_H\cos(\theta)]$$

...where the 'prime' notation indicates the rotated contact configuration of Figure 1-12 (b), and the expression is given in terms of a general rotation angle $\theta$. Clearly from this form, the smaller the angle is, the more accurately the measured voltage represents the electric field of interest. An outstanding problem, however, is the typical discrepancy between the magnitudes of the two electric fields. It is often the case that the longitudinal electric field can be far larger (potentially by orders of magnitude) than the transverse potential. Thus, a small misalignment often won't effect the transverse measurement much, but can lead to an erroneously large Hall voltage largely composed of signal from the unintended coupling of the longitudinal field into the measurement.

(a)



**Figure 1-12:** (a) Idealized lead placement, where endpoints of the contour integral relating measured voltage to the sample electric field are only sensitive to a voltage drop across only one such field. (b) Contacts rotated by 10 degrees to demonstrate how a single voltage measurement can couple to both electric fields.

(b)
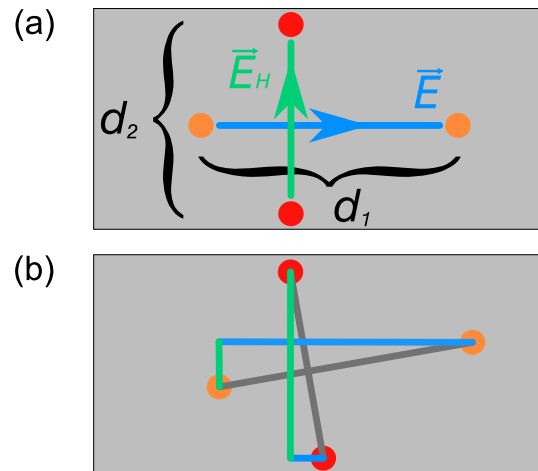


As described in Section 1.2.3.3, constant DC offsets can also complicate the interpretation of a measurement of the transverse voltage across a sample. One such source of such an offset arises from the thermoelectric effect occurring across the leads used to interface with a sample at cryogenic temperatures. Such wiring is necessarily subject to a large thermal gradient, and the resulting thermoelectric potential, though typically small in comparison to the longitudinal signal, is again often significant compared to the anticipated Hall voltage. It can be helpful collect these contributions to an *attempted* Hall voltage measurement into a single expression:

$$V'_H = d_2\,E\sin(\theta) + d_2\,E_H\cos(\theta) + V_{TE}$$

$$\Rightarrow V'_H = V_{Long.} + V_{Transv.} + V_{TE}$$

A final point of concern arises from the difficulty in accurately quantifying the lead spacing distances ($d_1$, $d_2$), which can be a significant source of uncertainty compared with the electronic measurement. As was the case for measurements of resistivity though, samples with the correct geometry can leverage the van der Pauw technique to more resolve some of these issues and more accurately quantify the 'Hall resistivity' and the derived quantities of interest therein.

### 1.3.2.1 Removing Unwanted Voltage Signals

For samples already meeting the criteria outlined in Section 1.2.3.1 the van der Pauw relation can similarly be applied to extract out the transverse component of sample resistivity. As might be expected, the voltage is now measured transverse to the direction of current flow. The goal now is to utilize the contact permutations in order to isolate the quantity of interest, the transverse (Hall) voltage, on its own. The first step is to remove the DC offset (assumed here to be due to the thermoelectric potential along the leads) by changing the direction of the current flow only.
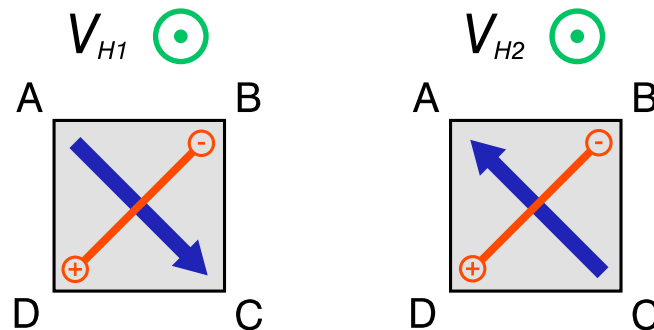


**Figure 1-13:** Lead configurations representing two measurements of the Hall voltage, where the direction of current flow is changed between the two. The magnetic field direction is indicated explicitly.

Since the sign of the constant thermoelectric contribution to the potential depends only on the thermal gradient along the wires, it should not switch under current reversal. Conversely, both the transverse and longitudinal potentials will change their sign under the polarity swap, thus:

$$V_{\text{H1}} - V_{\text{H2}} = (V_{\text{Long.}} + V_{\text{Transv.}} + V_{\text{TE}}) - (-V_{\text{Long.}} - V_{\text{Transv.}} + V_{\text{TE}})$$

$$\Rightarrow V_{\text{H1}} - V_{\text{H2}} = 2(V_{\text{Long.}} + V_{\text{Transv.}})$$

The difference between the voltages measured under the polarity swap yields an expression which has removed the constant offset component common to the measurements.

As shown previously, the Hall voltage component is also linear (i.e., an odd function) in magnetic field, so inverting the direction of the applied field results in two additional unique measurements, given by $V_{\text{H1x}}$ and $V_{\text{H2x}}$, as shown in Figure 1-14.
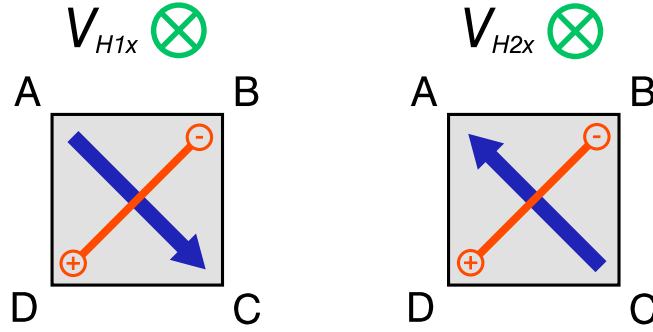
**Figure 1-14:** Lead configurations representing two measurements of the Hall voltage as shown in Figure 1-13, but where the direction of the magnetic field has been reversed.

These can be leveraged with the prior expression to yield:

$$(V_{H1} - V_{H2}) - (V_{H1x} - V_{H2x}) = 2\left[(V_{Long.} + V_{Transv.}) - (V_{Long.} - V_{Transv.})\right]$$

$$\Rightarrow (V_{H1} - V_{H2}) - (V_{H1x} - V_{H2x}) = 4\,V_{Transv.}$$

From this linear combination of four Hall voltage measurements, the transverse component (containing $E_H$, the actual quantity of interest) has been isolated. Writing this explicitly,

$$\tfrac{1}{4}\left[(V_{H1} - V_{H2}) - (V_{H1x} - V_{H2x})\right] = d_2\,\cos(\theta)\,E_H$$

Still, there remains the trouble of determining to high-precision the spatial orientation of the voltage contacts. To address that, we substitute the full expression for $E_H$:

$$\tfrac{1}{4}\left[(V_{H1} - V_{H2}) - (V_{H1x} - V_{H2x})\right] = d_2\,\cos(\theta)\left[-\frac{j\,B}{n\,q}\right]$$

Recall further that a requisite for characterizing samples via the van der Pauw technique was that the contacts lie at the edge of the sample. From this we can make the following inference about the contact geometry:
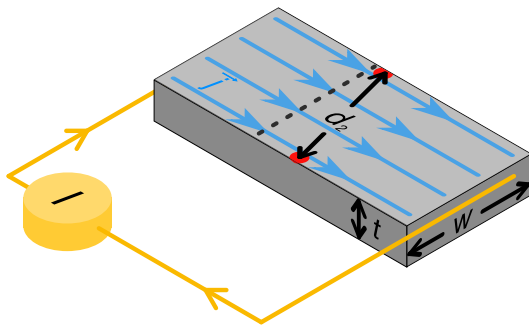


**Figure 1-15:** Depiction of the geometric relationship between the sample geometry and the voltage contact positioning.

For contacts placed at the edge, the $d_2\,\cos(\theta)$ expression is identically the width of the sample $w$. Assuming a uniform current distribution the unknown current density magnitude is $j = I/(w\,t)$. Substituting in these expressions,

$$\tfrac{1}{4}\left[(V_{H1} - V_{H2}) - (V_{H1x} - V_{H2x})\right] = w\left(\frac{I}{w\,t}\right)\left(-\frac{B}{n\,q}\right)$$

$$\Rightarrow R_H = -\frac{1}{n\,q} = \left(\frac{t}{I\,B}\right)\tfrac{1}{4}\left[(V_{H1} - V_{H2}) - (V_{H1x} - V_{H2x})\right]$$

In this form, the Hall coefficient has been characterized in terms of the four unique voltage measurements, the user-controlled values for sourced current and applied field, and the sample thickness. Given one of the conditions for the use of the van der Pauw technique for resistivity was a sample of uniform thickness, it is often the case that the thickness value is known to a high degree of accuracy.

### 1.3.2.2 Invoking Reciprocity

While the technique outlined above can be readily employed to conduct accurate measurements of the Hall coefficient, magnetic fields produced via superconducting solenoids require substantial time to reverse the field direction and acquire the second pair of voltages to isolate the transverse component of interest. Beyond the lengthy time required to collect the data, constantly changing the current in the magnet often drains liquid cryogen resources at a significantly higher rate, potentially making repeated measurements across the temperature range costly.

Fortunately, the *reverse magnetic field reciprocity* principle[2] (hereafter abbreviated as *RMFR*) can be leveraged to get around this difficulty. The principle states, in effect, that the measured voltage expected under a reversal of the magnetic field is the same voltage one measures under the *original field* when simultaneously exchanging the current source and voltage detection contacts. This is demonstrated schematically for the case of $V_{\mathrm{H1}}$ in Figure 1-16



**Figure 1-16:** Schematic depiction of the reverse magnetic field reciprocity principle. The key result relates the equivalence of the voltage/current contact permuted configuration ($V_{\mathrm{H8}}$) with the field-reversed configuration ($V_{\mathrm{H1x}}$).
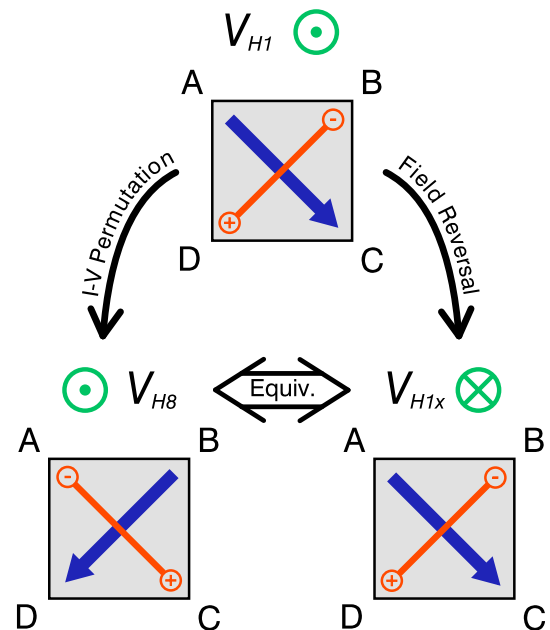
As such, a 'complete' measurement of the Hall coefficient is now evaluated using the updated voltage values, such that the field direction remains constant for each:

$$R_{\mathrm{H}} = -\frac{1}{n\,q} = \left(\frac{t}{I\,B}\right)\frac{1}{4}\left[(V_{\mathrm{H1}} - V_{\mathrm{H2}}) - (V_{\mathrm{H8}} - V_{\mathrm{H7}})\right]$$

...where these voltage configurations are given explicitly in Figure 1-17.

---

[2] H. H. Sample, et al, *Reverse-field reciprocity for conducting specimens in magnetic fields*, Journal of Applied Physics 61, (1987); DOI.
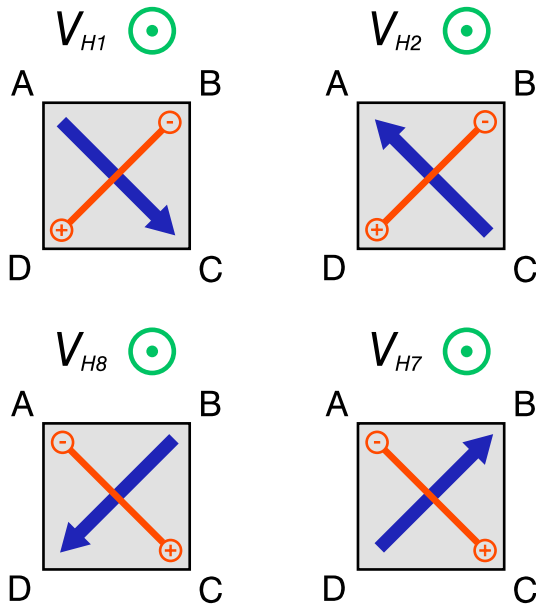
**Figure 1-17:** Set of four lead configurations for Hall measurements using RMFR.

As was the case for the resistivity measurement, due to the generalized symmetry of the sample, there exists a separate configuration (for the same applied field direction) which constitutes an independent measurement of the same physical quantity comprising the voltages $V_{H5}$, $V_{H6}$, $V_{H4}$, and $V_{H3}$:

$$R_{\mathrm{H}} = -\frac{1}{n\,q} = \left(\frac{t}{I\,B}\right)\frac{1}{4}[(V_{H5} - V_{H6}) - (V_{H4} - V_{H3})]$$

This can again be averaged with the prior expression if all eight voltage configurations are measured to reduce the uncertainty in the result:

$$R_H^{\mathrm{avg.}} = \frac{R_H(V_{H1/2/8/7}) + R_H(V_{H5/6/4/3})}{2}$$

Note that the reported Hall coefficient still depends on foreknowledge of the sample's thickness. If this is unknown, the extensive property $R_{\mathrm{H}}/t$, analogous to the sheet resistance discussed in the previous section, can still be quantified.

### 1.3.3    Reported Units

**Table 1-2:** Units of reported Hall properties.

| Property Name | Units | Description |
|---|---|---|
| $I$ | $[\mu\mathrm{A}]$ | Excitation |
| $H$ | $[\mathrm{Oe}]$ | Magnetic Field Strength |
| $R'_{\mathrm{H}}$ | $[\Omega \cdot \mathrm{cm}]/[\mathrm{Oe}]$ | 'Hall Coefficient ' |
| $V_{\mathrm{H}}/I$ | $[\Omega]$ | Hall Resistance |
| $n$ | $[\mathrm{cm}]^{-3}$ | Carrier Density[4] |

Note that the units of the reported quantities are also always indicated by the column titles within header of the `.dat` file as well.

---

[4] As mentioned in Section 1.3.1 this analysis assumes the simple model of a single type of charge carrier.

### 1.3.3.1 Comments on the Hall Coefficient Units

Some care must be taken in handling the as-reported values of the Hall coefficient; recalling the definition from Section 1.3.2.2:

$$R_{\mathrm{H}} = -\frac{V_{\mathrm{Av.}}}{I}\frac{t}{B}$$

...based on the nominal SI units for voltage, length, current, and magnetic flux density, then the units of the Hall coefficient in SI should be:

$$[R_{\mathrm{H}}] = \frac{[\mathrm{V}]}{[\mathrm{A}]}\frac{[\mathrm{m}]}{[\mathrm{T}]} = \frac{[\Omega]\,[\mathrm{m}]}{[\mathrm{T}]}$$

Immediately this form raises questions when compared with the units of the reported Hall coefficient given in Table 1-2; both have dimensions of "resistance-length" in the numerator, but their denominators differ: oersteds are the *CGS* units of $H$ ('magnetic field strength'), while tesla are the *SI* units of $B$ ('magnetic flux density'). It is the latter which follows from the derivation outlined in Section 1.3.1, and so represents the correct units in SI for the quantity assigned the label "Hall coefficient." As such, we note here explicitly that the reported quantity *is not strictly the Hall coefficient*, but something closely related:

$$R'_{\mathrm{H}} = -\frac{V_{\mathrm{Av.}}}{I}\frac{t}{H}$$

At the crux of this discrepancy is the relation between these two quantities both casually termed 'magnetic field', and a third, called 'volume magnetization'. In the SI system of units, the are related by:

$$B = \mu_0(H + M)$$

At the strength of fields typically applied to properly resolve the Hall coefficient (10s of $\mathrm{kOe}$, or many 100s of $\mathrm{kA/m}$) the sample's own magnetization contribution via $M$ is treated as negligible, so the approximation can be made:

$$B \approx \mu_0 H$$

$$\Rightarrow R_{\mathrm{H}} = -\frac{V_{\mathrm{Av.}}}{I}\frac{t}{\mu_0 H}$$

The units remain unchanged, but the expression is now cast exclusively in terms of explicitly controlled (excitation, applied field) and measured (voltage, thickness) quantities. This reveals the relation between the reported quantity and the 'true' Hall coefficient, again assuming a negligible magnetization contribution:

$$R_{\mathrm{H}} = \left(\frac{1}{\mu_0}\right) R'_{\mathrm{H}}$$

If one chooses to cast the quantity $\mu_0 H$ in CGS units, the vacuum permeability has unity magnitude, but effectively transforms the field units from $[\mathrm{Oe}]$ to $[\mathrm{G}]$. From there, the CGS-to-SI conversion factor between gauss to tesla ($10^{-4}$) and centimeters to meters ($10^{-2}$) are straightforward to apply, resulting in a purely SI representation of the Hall coefficient.

For the sake of completeness: if $\mu_0 H$ is cast in SI instead, the definition[5] of the comparability in that system is given by $\mu_0 = 4\pi \cdot 10^{-7}\ \mathrm{H/m}$. This, along with the conversion factors of centimeters to meters ($10^{-2}$) and oersted to amps-per-meter ($10^{-3}/4\pi$), conspire to produce an identical scaling prefactor- the one noted in Table 1-3.

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[5] Where the slight adjustments owing to the 2019 redefinition are understood to be present but not explicitly shown.

## 1.3.3.2 Converting to SI

Table 1-3 provides the relevant conversion factors for translating the constituent and derived units of the reported quantities into SI. The conversation is defined such that multiplying a value in the 'Reported Units' by the conversion factor will a result in the proper magnitude for the same quantity in 'SI Units'.

**Table 1-3:** Conversion factors for reported Hall properties.

| Quantity | Symbol | Reported Units | Conversion Factor | SI Units | Notes |
|---|---|---|---|---|---|
| Magnetic Field | $H$ | $[\mathrm{Oe}]$ | $\dfrac{10^3}{4\pi}$ | $[\mathrm{A}]/[\mathrm{m}]$ | |
| Hall Coefficient | $R_\mathrm{H}$ | $[\Omega \cdot \mathrm{cm}]/[\mathrm{Oe}]$ | $10^2$ | $[\Omega \cdot \mathrm{m}]/[\mathrm{T}]$ | Assumes negligible magnetization contribution |
| Hall Coefficient | $R_\mathrm{H}$ | $[\Omega \cdot \mathrm{cm}]/[\mathrm{Oe}]$ | $10^2$ | $[\mathrm{m}^3]/[\mathrm{C}]$ | Assumes negligible magnetization contribution |
| Carrier Density | $n$ | $[\mathrm{cm}]^{-3}$ | $10^6$ | $[\mathrm{m}]^{-3}$ | Assumes single carrier type with a charge of $e$. |

Note the two SI derived units provided for the Hall coefficient. They can be shown to be equivalent:

Multiplication by one,

$$1\frac{[\Omega \cdot m]}{[T]} = 1\frac{[\Omega \cdot m]}{[T]}\frac{[A]^2}{[A]^2}$$

definition of an ampere,

$$= 1\frac{[m]}{[T]}\frac{[\Omega]}{[A]}\frac{[A]^2}{[A]}\frac{[s]}{[C]}$$

definition of a watt (for ohmic elements),

$$= 1\frac{[m]}{[C]}\frac{[W]}{[A]}\frac{[s]}{[T]}$$

definition of a joule,

$$= 1\frac{[m]}{[C]}\frac{[m]}{[A]}\frac{[N]}{}\frac{1}{[T]}$$

definition of a tesla,

$$= 1\frac{[m]^2}{[C]}\frac{[N]}{[A]}\frac{[A]}{[N]}\frac{[m]}{}$$

after cancellations,

$$1\frac{[\Omega \cdot m]}{[T]} = 1\frac{[m]^3}{[C]}$$

As such, they share the same prefactor in Table 1-3 for conversion from the reported quantity/unit.

# 1.4 Carrier Mobility

The two quantities of interest discussed in Section 1.2 and Section 1.3 are useful when measured together as they can be used to calculate the carrier mobility[6] in the sample. This parameter is defined as

$$\mu_{\mathrm{H}} = R_{\mathrm{H}}/\rho$$

If written in terms of the sheet resistance, this expression becomes:

$$\mu_{\mathrm{H}} = \left(\frac{R_{\mathrm{H}}}{t}\right)\frac{1}{R_S}$$

The quantity in the parentheses and the sheet resistance are each deduced directly by voltage averaging and proper scaling by the sourced current and applied field- no other parameters are needed. As such, the mobility can be accurately evaluated with *no prior knowledge* of the sample's thickness.

## 1.4.1 Reported Units

**Table 1-4:** Units of reported Hall mobility.

| Property Name | Units | Description |
|---|---|---|
| $\mu_{\mathrm{H}}$ | $[\mathrm{cm}^2]/[\mathrm{V}\cdot\mathrm{s}]$ | Carrier Mobility |

## 1.4.2 Converting to SI

Table 1-5 provides the relevant conversion factors for translating the constituent and derived units of the reported quantities into SI. The conversation is defined such that multiplying a value in the 'Reported Units' by the conversion factor will a result in the proper magnitude for the same quantity in 'SI Units'.

**Table 1-5:** Conversion factor for reported mobility

| Quantity | Symbol | Reported Units | Conversion Factor | SI Units | Notes |
|---|---|---|---|---|---|
| Carrier Mobility | $\mu_{\mathrm{H}}$ | $[\mathrm{cm}^2]/[\mathrm{V}\cdot\mathrm{s}]$ | $10^{-4}$ | $[\mathrm{m}^2]/[\mathrm{V}\cdot\mathrm{s}]$ | |

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[6] The carrier mobility, when determined in this way, is also sometimes labeled as the 'Hall mobility'.

# Hardware Descriptions

## 2.1 Automated Switch Box

The switch box (*Model ASB102*) is the primary component of the van der Pauw - Hall Option. When placed in-line with the nominal 4-probe measurement circuit a series of switching relays inside allow for the current and voltage contacts to be permuted. This enables the measurement circuit to be reconfigured via remote control to the achieve the lead mappings required to properly execute van der Pauw resistivity and Hall measurements. Since no hands-on interaction from the user is needed, these measurements can be acquired with much greater efficiency.

### 2.1.1 Front Panel Indicators
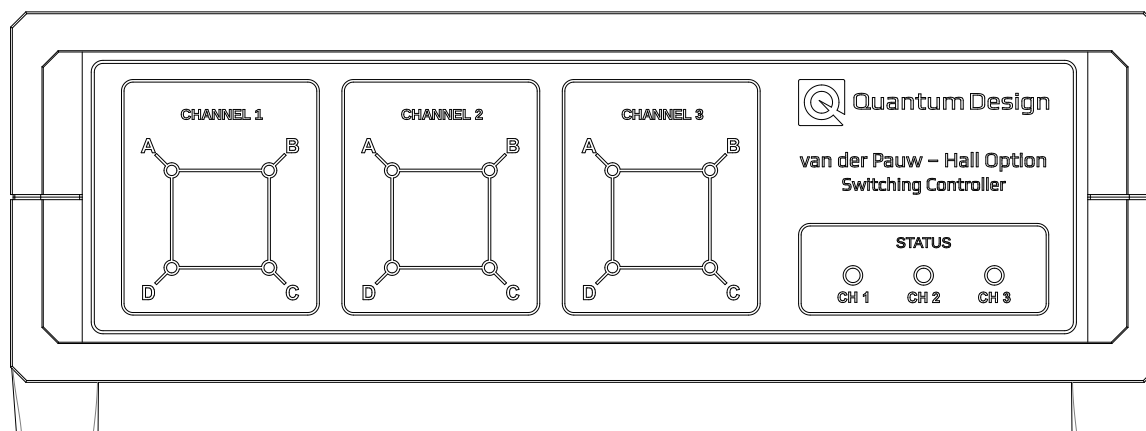


**Figure 2-1:** Switch box front panel.

The front panel of the switch box contains several indicators. At left, the schematics represent the samples connected to the three available channels. The corners are lit to provide a real-time indicator of the current configuration of the current and voltage leads at the sample. Yellow coloring indicates current sourcing, while green indicates voltage detection. The brighter of the pair corresponds to positive polarity while the dimmer is negative. An example corresponding to the $V_1$ configuration is shown in Figure 2-2. Note that these indicators couple directly to the physical state of the relay switches, not the programmed switching state (though the two are identical under normal operating conditions).
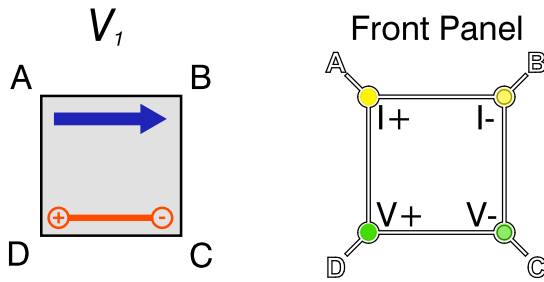
**Figure 2-2:** Front panel lead configuration indicators. The yellow pair indicates current, green is voltage. The brighter indicator corresponds to positive polarity.

At right a set of three 'Status' indicators during normal operation provide a succinct way to ascertain the measurement being made in the present lead configuration. Table 2-1 relates the meaning of a given color to the lead configuration.

**Table 2-1:** Front panel status indicator color interpretation.

| Color | Measurement Type | Rotation (Deg.) | Current |
|:---:|:---:|:---:|:---|
| Green | Resistivity | 0 | Default |
| Blue | Resistivity | 90/180/270 | Default |
| Red | Resistivity | 0/90/180/270 | Reversed |
| Cyan | Hall | 0/90/180/270 | Default |
| Violet | Hall | 0/90/180/270 | Reversed |

If the USB connection has not been made, these status indicators are unlit. If the USB connection is established but the switching relays are unpowered (more information on this in the following Section 2.1.2), these status lights will illuminate in a slow 'scrolling' pattern, alternating between blue and green, as an indicator of the error state.

## 2.1.2   Rear Panel
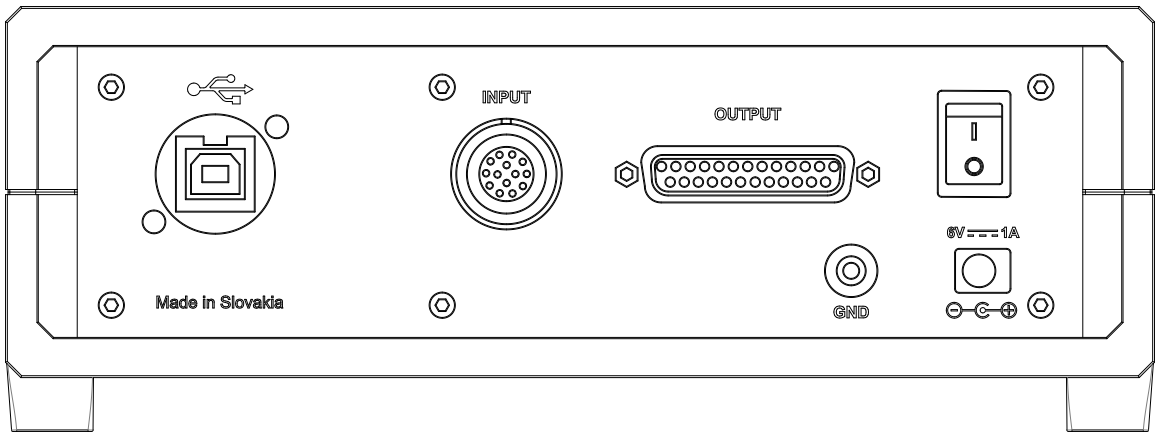


**Figure 2-3:** Switch box rear panel.

The rear panel contains the necessary ports to power and use the switch box. At left, the USB interface utilizes a Type-B connector to facilitate serial communication between the MultiVu PC and the microcontroller inside of the switch box. While the microcontroller is powered over this USB cable, note that the *switching relays are not*. These require the included additional power supply to be connected (lower right), and the rocker switch (upper right) to be in the 'on' position.

With the switch box being placed in-line with the measurement circuit there is some ambiguity in interpreting the meaning of the 'Input' and 'Output' connectors on the back panel, so they are stated here explicitly. The standard User Bridge Cable (QD P/N: 3084-005-01) coming from the *cryostat* connects to the terminal labeled 'Output'. From there, a second User Bridge Cable coming from the 'Input' connector is routed to the *BRT module*. A cabling diagram can be found in Figure 4-2.

Finally, the GND banana plug jack gives the user access to the ground of the switch box. This ground connects to both the inner metallic shield of the switch box chassis and to pin 13 of the DB-25 'Output' connector. Pin 13 is also connected to the cable shielding of a standard User Bridge Cable, so for operation with Quantum Design supplied cables, this grounding jack is not typically used. For further details regarding the bridge cable, see Table C-1.

### 2.1.3 Switching Operation Details

When a change in the switching state is initiated, the following procedure occurs:

    **a.** The current leads in the designated channel are shorted to one another.

    **b.** The proper relays are triggered to achieve the updated routing state.

    **c.** Current flow is re-enabled for the updated switching state.

    **d.** A signal is returned to the PC indicated the switching operation was successful.

This ensures the sample and relays are protected from any inadvertent exposure to a live excitation source during switching. When used with the van der Pauw - Hall Option software, the excitation is deactivated during switching, such that there are multiple redundancies to protect the sample and hardware.

## 2.2 Resistivity Puck

For measurements with the van der Pauw - Hall Option, samples should be mounted on the same Resistivity puck used with the DC Resistivity and Electrical Transport Options. A sample can be wired to each of the three channels according to the scheme indicated in Figure 4-1. It is important to wire samples in this particular way as the switch box does not permit *arbitrary* contact mapping. For more information on sample mounting, see Section 4.1.1.3.

## 2.3 Cabling

The option utilizes two User Bridge Cables (QD Part No. 3084-005-01) for interconnects between the cryostat and the electronics. Details on the wiring of these cables can be found in Section C.2.

## 2.4 BRT CAN Module

The BRT CAN module (Model CM-L) acts as both the current source and voltmeter for the purposes of the van der Pauw and Hall measurements utilizing the internal resistance bridge card. Since only the resistance bridge functionality of the module is employed by the vdP-Hall Option, only port JL-1 'Bridge' is used. The option software handles the synchronization between the updating of the switching state with the triggering of a measurement at the BRT module.

Since the resistance bridge is itself capable of reversing the polarity of its own sourced DC current, this operation can be handled internally within the BRT module. Where appropriate, this internal switching is used instead of achieving current reversal by permuting the contacts. This saves the user some time by speeding the measurement, as the internal BRT current switching is somewhat faster than the relays in the switch box.

# Software Overview

## 3.1     Getting Started

The latest versions of both MultiVu and the van der Pauw-Hall Option software can always be found on the Quantum Design website.[1] Check occasionally to confirm the latest version is installed, as updates can contain additional features, ease-of-use improvements, or important bug fixes.

The van der Pauw-Hall Option software can be activated by browsing to the Option Manager via the menu items **Utilities>Activate Option…**, choosing 'van der Pauw-Hall', and clicking **Activate**.
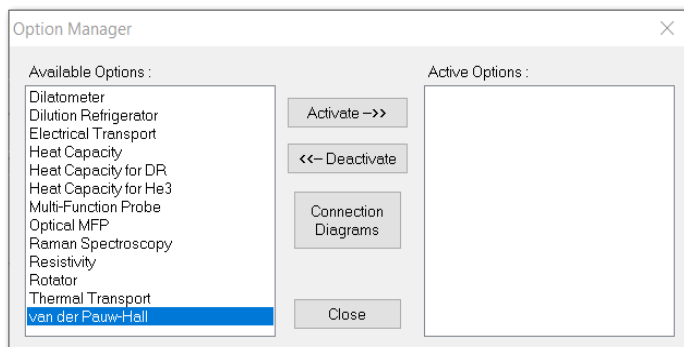


**Figure 3-1:** Option Manager window.

## 3.2     Interface Walkthrough

When the van der Pauw-Hall Option is first activated, the main control window and the Log window both automatically appear. Their functions as well as that of the primary measurement dialog windows are described below.

### 3.2.1     van der Pauw-Hall Log Window

The van der Pauw-Hall Log window displays various status updates generated by the option software. As part of the initialization procedure, the present software version is declared and communication with the BRT module and switching box is initiated. If the software detects any errors, they are reported here.

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[1] Under the 'Software Upgrades' section:
https://www.qdusa.com/support/software_upgrades.html

**Figure 3-2:** van der Pauw-Hall Log window.
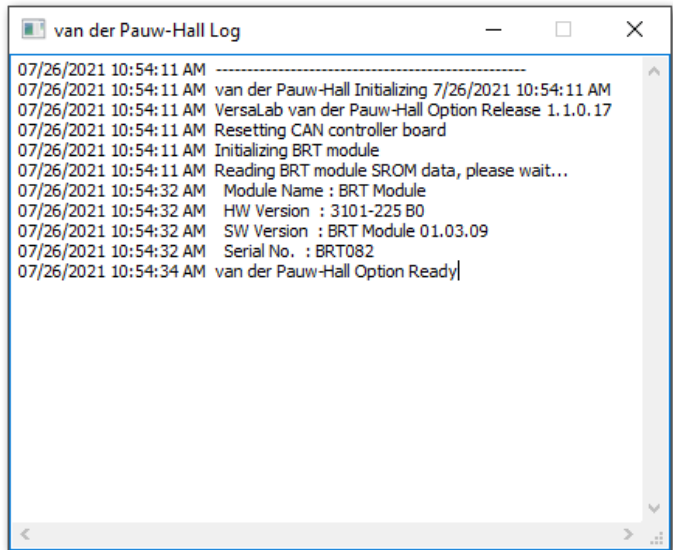
During a measurement, this log will continually record key events (e.g., changing the data file, starting a measurement, etc.). Anything appearing in the Log window is also written to the `\vanderPauwHall\LogFiles\vdpHallLog.txt` file in case it is needed for later review.

The Log window can always be recalled to the foreground with the menu command **View>van der Pauw-Hall Log**.

### 3.2.2 van der Pauw-Hall Option Control Window

The main window for controlling the option is shown in Figure 3-3
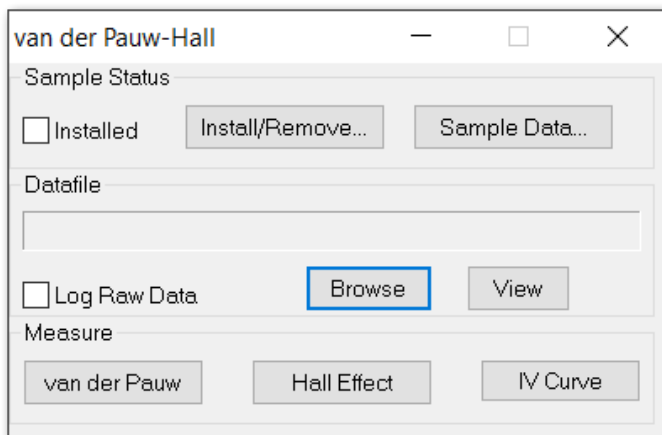


**Figure 3-3:** Main van der Pauw-Hall window for option control.

#### 3.2.2.1 Sample Status

The **Install**/**Remove** button triggers the associated wizard which will assist the user with the proper procedure in venting the sample space, installing the puck, and purging the sample space. Upon completion, the Installed checkbox indicates a sample is present. Alternatively, this operation can be performed manually, but the Installed indicator will not be present.

If a datafile is already active, the **Sample Data...** button allows the user to view the sample names and thicknesses values for each channel as input by the user when the `.dat` file was created.

#### 3.2.2.2 Datafile

The field here displays the currently active data file in which measurement results will be recorded. This file can be changed using the **Browse** button, prompting the user to again enter the sample names and thickness values. To

plot the data of the active file in MultiVu, use the **View** button.

### 3.2.2.3 Measure

Three immediate 'Quick Measurement' dialogs can be accessed from this pane, but their function is sufficiently complex they are fully detailed in the subsequent sections: **van der Pauw** resistivity (Section 3.2.3), **Hall Effect** (Section 3.2.4), and **IV Curve**s (Section 3.2.5).

## 3.2.3 van der Pauw Resistivity

The main dialog for configuring a measurement of a sample's bulk/sheet resistivity using the van der Pauw technique is shown in Figure 3-4. The theoretical basis for this method is described in Section 1.2.3.



**Figure 3-4:** van der Pauw resistivity Quick Measure dialog.

The checkboxes in the left column indicate which Channels should be active for the measurement. The Configuration for the measurement is determined by the choice of option in the drop-down menu. For each choice of configuration the software will collect a unique set of voltage measurements corresponding to a series of different lead permutations. A detailed explanation of each configuration mode in given in the next sections. For further information, see also Figure C-3 for schematic diagrams of the voltage indices listed, and Table C-2 for more details regarding the ASB state codes.

For each lead permutation, the sample is sourced with the user-specified excitation current and the corresponding voltage is recorded; this is repeated and averaged across the number specified by the user in the Readings field. These averaged voltages are then appropriately used in evaluating the van der Pauw relation to extract the sample's sheet resistance and (using the value of thickness supplied by the user) the bulk/volume resistivity. For the Quick Measure dialog, the latter is reported in the adjacent field for quick tests.

Other diagnostic parameters (Readings completed, Estimated and Elapsed Time to complete the measurement, the system-reported Position, Temperature, and Field during the measurement) are also included.

**Measure** initiates the measurement as-configured, while **Save** will record a the prior result to the active **.dat/.raw** files. **Close** will return focus to the main control window.

### 3.2.3.1 vdP(quick) Configuration

In this configuration two lead permutations probing the sample's longitudinal response are used; one is rotated 90 degrees from the other, similar to the experiment originally described by van der Pauw. The only difference is the measurement of the voltage for each configuration is conducted while alternating the polarity of the sourced current.

The reason for this, articulated in Section 1.2.3.3, is to remove DC offsets to improve the measurement accuracy. By alternating the current polarity in the measurement electronics (versus using slower the ASB relays) the measurement speed is improved somewhat.

This configuration is recommended for most typical measurements.

**Table 3-1:** vdP(quick) measurement sequence.

| Voltage Index | ASB State (Ch1/2/3) | Notes |
|---|---|---|
| $V_1$ | 0x1000 / 0x2000 / 0x4000 | Current polarity averaged; result includes $V_2$ |
| $V_3$ | 0x1002 / 0x2020 / 0x4200 | Current polarity averaged; result includes $V_4$ |

The final evaluation of the resistivity uses the following expression:

$$\rho_{\text{quick}} = \frac{\pi}{\ln(2)} \frac{t}{2I} \left( \left[ \frac{V_1 - V_2}{2} \right] + \left[ \frac{V_3 - V_4}{2} \right] \right) f\left( \frac{V_1 - V_2}{V_3 - V_4} \right)$$

### 3.2.3.2 vdP(average) Configuration

This configuration is partially identical to the vdP (quick) described just prior, but it includes a second unique measure of the resistivity using further rotations of the contact field (see Section 1.2.3.3

In this way, the uncertainty is further reduced by averaging two complete, independent quantifications of the sheet resistivity. This configuration is only recommended where the user is willing to effectively double the measurement time in exchange for the root-2 reduction in uncertainty in the reported result.

**Table 3-2:** vdP(average) measurement sequence.

| Voltage Index | ASB State (Ch1/2/3) | Notes |
|---|---|---|
| $V_1$ | 0x1000 / 0x2000 / 0x4000 | Current polarity averaged; result includes $V_2$ |
| $V_3$ | 0x1002 / 0x2020 / 0x4200 | Current polarity averaged; result includes $V_4$ |
| $V_5$ | 0x1004 / 0x2040 / 0x4400 | Current polarity averaged; result includes $V_6$ |
| $V_7$ | 0x1006 / 0x2060 / 0x4600 | Current polarity averaged; result includes $V_8$ |

The final evaluation of the resistivity uses the following expression:

$$\rho(V_1, \ldots, V_4) = \frac{\pi}{\ln(2)} \frac{t}{2I} \left( \left[ \frac{V_1 - V_2}{2} \right] + \left[ \frac{V_3 - V_4}{2} \right] \right) f\left( \frac{V_1 - V_2}{V_3 - V_4} \right)$$

$$\rho(V_5, \ldots, V_8) = \frac{\pi}{\ln(2)} \frac{t}{2I} \left( \left[ \frac{V_5 - V_6}{2} \right] + \left[ \frac{V_7 - V_8}{2} \right] \right) f\left( \frac{V_5 - V_6}{V_7 - V_8} \right)$$

$$\rho_{\text{average}} = \frac{\rho(V_1, \ldots, V_4) + \rho(V_5, \ldots, V_8)}{2}$$

### 3.2.3.3 vdP(classic)

As in vdP (quick), for this configuration two lead permutations probing the sample's longitudinal response are evaluated; one is rotated 90 degrees from the other, but in this case only a *DC* measurement is executed. This makes the result more prone to error from systematic DC offsets, and it is no faster than vdP(quick).

It is included only to give users the opportunity to compare with vdP (quick), to provide a sense of the potential errors resulting from spurious constant DC signals.

**Table 3-3:** vdP(classic) measurement sequence.

| Voltage Index | ASB State (Ch1/2/3) | Notes |
|---|---|---|
| $V_1$ | 0x1000 / 0x2000 / 0x4000 | DC measure only. |

| Voltage Index | ASB State (Ch1/2/3) | Notes |
|---|---|---|
| $V_3$ | 0x1002 / 0x2020 / 0x4200 | DC measure only. |

The final evaluation of the resistivity uses the following expression:

$$\rho_{\text{classic}} = \frac{\pi}{\ln(2)} \frac{t}{2I} \left( \frac{V_1 + V_3}{2} \right) f\left( \frac{V_1}{V_3} \right)$$

## 3.2.4  Hall Effect

The main dialog for configuring a measurement of a sample's Hall coefficient is shown in Figure 3-5. The theoretical basis for this method is described in Section 1.3.2.
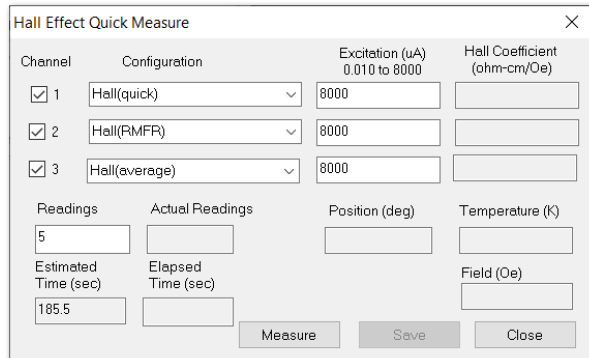


**Figure 3-5:** Hall Effect Quick Measure dialog.

The checkboxes in the left column indicate which Channels should be active for the measurement. The Configuration for the measurement is determined by the choice of option in the drop-down menu. For each choice of configuration the software will collect a unique set of voltage measurements corresponding to a series of different lead permutations. A detailed explanation of each configuration mode can be found in the following sections (see Figure C-4 for schematic diagrams of the voltage indices listed, and Table C-2 for more details regarding the ASB switch state).

For each lead permutation, the sample is sourced with the user-specified excitation current and the corresponding voltage is recorded; this is repeated and averaged across the number specified by the user in the Readings field. These averaged voltages are then added in linear combinations such that only the desired transverse component of the measured voltage remains, yielding an accurate measure of the Hall coefficient. For the Quick Measure dialog this value is reported in the adjacent field for testing.

Other diagnostic parameters (Readings completed, Estimated and Elapsed Time to complete the measurement, the system-reported Position, Temperature, and Field during the measurement) are also included.

**Measure** initiates the measurement as-configured, while **Save** will record a the prior result to the active `.dat/.raw` files. **Close** will return focus to the main control window.

### 3.2.4.1 Hall(quick) Configuration

In this configuration a single lead configuration probing the sample's transverse voltage response is evaluated. The voltage measurement is conducted while alternating the polarity of the sourced current to remove DC offsets to improve the measurement accuracy. By alternating the current polarity in the measurement electronics (versus using slower the ASB relays) the measurement speed is improved somewhat.

This configuration is recommended for fast, rough checks of a sample's response only, since it includes no technique to extract any component of the longitudinal response which might be included due to lead placement and/or sample geometry (see Section 1.3.2.1).

**Table 3-4:** Hall(quick) measurement sequence.

| Voltage Index | ASB State (Ch1/2/3) | Notes |
|---|---|---|
| $V_{H1}$ | 0x1008 / 0x2080 / 0x4800 | Current polarity averaged; result includes $V_{H2}$ |

The final evaluation of the resistivity uses the following expression:

$$R_{\text{H(quick)}} = \left(\frac{t}{I\,B}\right)\left[\frac{V_{H1} - V_{H2}}{2}\right]$$

### 3.2.4.2 Hall(RMFR) Configuration

In order to fully isolate the transverse component of the voltage, it would ordinarily be necessary to repeat the Hall (quick) measurement with the applied field vector pointing in the opposite direction. By leveraging the reverse magnetic field reciprocity (RMFR) principal this constraint is eased and the field can remain static, but specific lead permutations are needed to produce the correct corresponding voltages (see Section 1.3.2.2).

As a result, the Hall (quick) configuration is still measured, in addition to its field-reversed RMFR analog, under alternating current polarity. These data are averaged to yield a voltage originating purely from the sample's manifestation of the Hall effect.

This configuration is recommended for most measurements, as it is the fastest version which still removes both constant DC offsets and longitudinal signals, each of which is potentially much larger than the transverse voltage response of principal interest.

**Table 3-5:** Hall(RMFR) measurement sequence.

| Voltage Index | ASB State (Ch1/2/3) | Notes |
|---|---|---|
| $V_{H1}$ | 0x1008 / 0x2080 / 0x4800 | Current polarity averaged; result includes $V_{H2}$ |
| $V_{H8}$ | 0x100F / 0x20F0 / 0x4F00 | Current polarity averaged; result includes $V_{H7}$ |

The final evaluation of the resistivity uses the following expression:

$$R_{\text{H(RMFR)}} = \left(\frac{t}{I\,B}\right)\frac{1}{4}[(V_{H1} - V_{H2}) - (V_{H8} - V_{H7})]$$

### 3.2.4.3 Hall(average) Configuration

To further improve on the Hall (RMFR) measurement, two independent measures of the Hall coefficient using this methodology can be averaged to achieve a modest reduction in the uncertainty. The prior Hall (RMFR) measurement is performed, then repeated with a separate set of voltages stemming from a nominal 180 degree rotation, its current reversal, and the field-reversed RMFR analogs of those permutations.

This configuration is only recommended where the user is willing to effectively double the Hall (RMFR) measurement time in exchange for the root-2 reduction in uncertainty in the reported result.

**Table 3-6:** Hall(average) measurement sequence.

| Voltage Index | ASB State (Ch1/2/3) | Notes |
|---|---|---|
| $V_{H1}$ | 0x1008 / 0x2080 / 0x4800 | Current polarity averaged; result includes $V_{H2}$ |
| $V_{H8}$ | 0x100F / 0x20F0 / 0x4F00 | Current polarity averaged; result includes $V_{H7}$ |
| $V_{H5}$ | 0x100C / 0x20C0 / 0x4C00 | Current polarity averaged; result includes $V_{H6}$ |
| $V_{H4}$ | 0x100B / 0x20B0 / 0x4B00 | Current polarity averaged; result includes $V_{H3}$ |

The final evaluation of the resistivity uses the following expression:

$$R_{\mathrm{H}}^{(V_{\mathrm{H1}}/V_{\mathrm{H2}}/V_{\mathrm{H8}}/V_{\mathrm{H7}})} = \left(\frac{t}{I\,B}\right)\frac{1}{4}\left[(V_{\mathrm{H1}} - V_{\mathrm{H2}}) - (V_{\mathrm{H8}} - V_{\mathrm{H7}})\right]$$

$$R_{\mathrm{H}}^{(V_{\mathrm{H5}}/V_{\mathrm{H6}}/V_{\mathrm{H4}}/V_{\mathrm{H3}})} = \left(\frac{t}{I\,B}\right)\frac{1}{4}\left[(V_{\mathrm{H5}} - V_{\mathrm{H6}}) - (V_{\mathrm{H4}} - V_{\mathrm{H3}})\right]$$

$$R_{H(average)} = \frac{R_{\mathrm{H}}^{(V_{\mathrm{H1}}/V_{\mathrm{H2}}/V_{\mathrm{H8}}/V_{\mathrm{H7}})} + R_{\mathrm{H}}^{(V_{\mathrm{H5}}/V_{\mathrm{H6}}/V_{\mathrm{H4}}/V_{\mathrm{H3}})}}{2}$$

## 3.2.5 IV Curves

The main dialog for configuring the collection of an IV curve is shown in Figure 3-6. This is a helpful utility to verify, especially upon installation, that the contacts to the sample remain ohmic, providing some additional confidence in the reported data.



**Figure 3-6:** IV Curve Quick Measure dialog
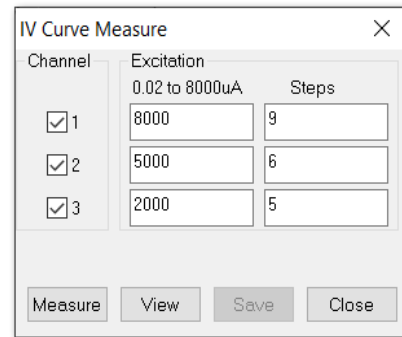
The checkboxes in the left column indicate which Channels should be active for the measurement, while the Excitation limit in the center column sets the maximum current sourced to the sample. The Steps field determines the number of linearly spaced points to be sampled the current space, starting with zero[2] and ending at the user-specified maximum.

**Measure** initiates the measurement as-configured, while **Save** will record a the prior result to the active `.ivraw` file. **View** brings the current IV curve to the fore, and**Close** will return focus to the main control window.

## 3.3 Sequence Command List

Activating the van der Pauw-Hall Option software causes a new set of sequence commands to be added to the list shown in the **View>Sequence Command Bar** area under the Measurement Commands listing (shown in Figure 3-7).
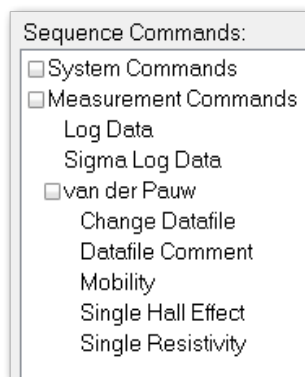


**Figure 3-7:** Available van der Pauw-Hall measurement commands listing.

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[2] A true measurement at null excitation is not actually performed. A 'dummy' point at (0,0) is used for all IV curves instead.

The functionality of these commands is described individually in the order they are listed.

## 3.3.1   Change Datafile

To save the measured data, it is necessary to specify where the option software should write the results. This can be set by hand using the **Browse** button in the main control dialog (see Section 3.2.2.2), but it can also be updated systematically using the **Change Datafile** sequence command.

**Figure 3-8:** Datafile tab of the Change Datafile sequence command configuration.
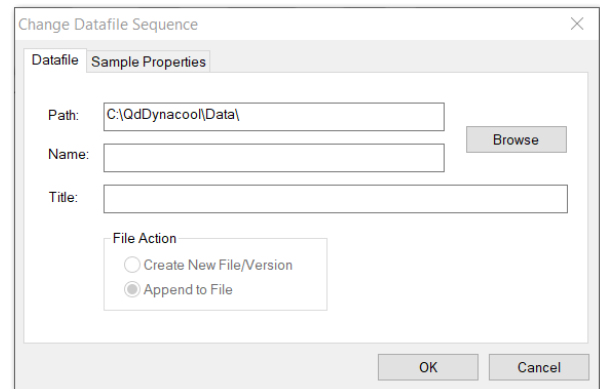
The New Datafile command allows the user to specify a location (Path), Name, and Title for the file using the **Browse** button. If the file does not already exist, it will be created upon execution of the sequence command. If a file with a matching name already exists at the specified path, the setting under the File Action pane determines what occurs. **Create New File**/**Version** will cause a new file to be created with a matching name and _00001 added to the end (running the same command subsequent times will continue creating new files, incrementing the appended counter by one each time). **Append to File** will simply continue adding data to the already-extant file.

Proper calculation of the bulk resistivity and Hall coefficient values requires *a priori* knowledge of the sample's thickness, so there is a separate Sample Properties tab, shown in Figure 3-9, to provide the software with this information. The sample identifier can be optionally written in the Name field, while the thickness must be supplied for accurate values of the bulk resistivity and Hall coefficient. If the thickness is unknown the *mobility* can still be accurately determined as the default (or any) thickness parameter drops out in the calculation (see Section 1.4).
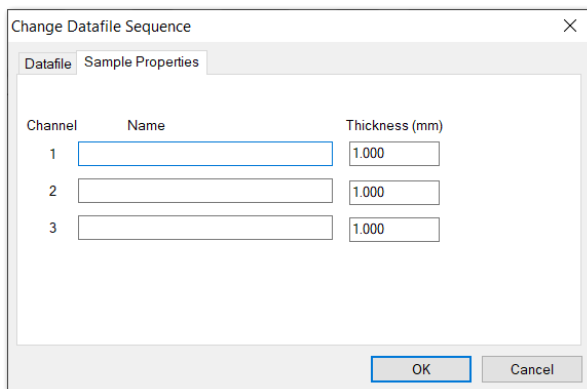
**Figure 3-9:** Sample Properties tab of the Change Datafile sequence command configuration.

## 3.3.2   Datafile Comment

If it is helpful to include some notes or additional information in-line with the van der Pauw-Hall data, this command allows the user to add a string of text. When written to the .dat file, it also includes the time stamp.

**Figure 3-10:** Datafile Comment sequence command dialog.
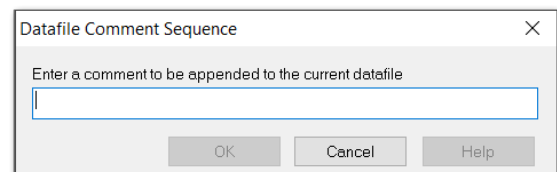
### 3.3.3 Mobility

The Mobility command combines the functionality of both van der Pauw resistivity and Hall effect measurements into a single sequence command. When both are selected, this enables the additional calculation of their ratio to directly report the Hall mobility.

#### 3.3.3.1 Settings Tab

The first tab of the configuration window, shown in Figure 3-11, allows the user to select which Channels will be active. For the active channels, the user can select which measurements will be conducted.

If the user opts to collect diagnostic IV curves for contact performance diagnostics those are also configured on this front pane. These data are collected and recorded as described in Section 3.2.5.
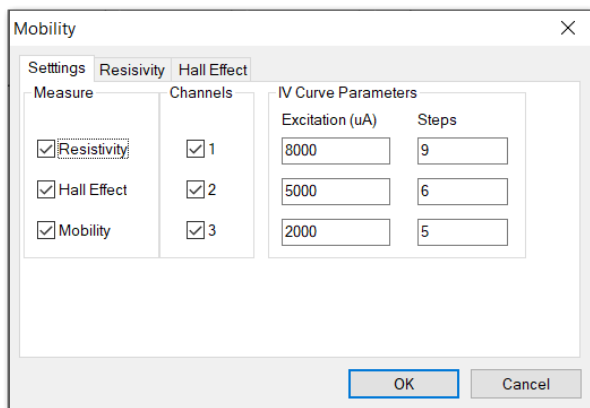


**Figure 3-11:** Mobility sequence command dialog, Settings tab.

#### 3.3.3.2 Resistivity Tab

This tab functions identically to that found in the associated Quick Measure dialog discussed in Section 3.2.3. The only additional option allows the user to trigger an IV curve measurement before the measurement, if desired.



**Figure 3-12:** Mobility sequence command dialog, Resistivity tab.
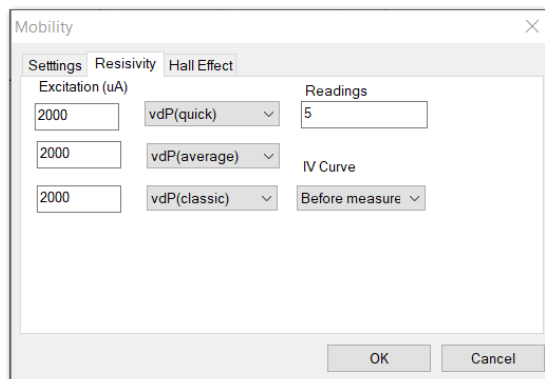
#### 3.3.3.3 Hall Effect Tab

This tab functions similarly to that found in the associated Quick Measure dialog discussed in Section 3.2.4. An additional option allows the user to trigger an IV curve measurement before the full or individual measurements, if desired.
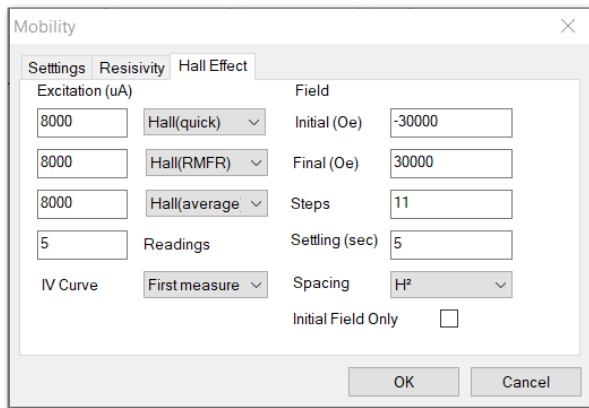
**Figure 3-13:** Mobility sequence command dialog, Hall Effect tab.

The primary difference is in how the magnetic field parameter is treated. To execute only a single measurement of the Hall effect at a particular field, select the **Initial Field Only** checkbox- the Hall measurement will be performed only at the magnetic field specified in the Initial (Oe) input box.

For samples with small Hall voltages the signal to noise ratio can be poor. In such cases, a single-point measurement may not be a reliable indicator of the true Hall response. Historically, a technique to overcome this challenge has been to measure the Hall voltage at various values of the applied magnetic field and fit the resulting curve to a straight line, the slope of which is proportional to the Hall coefficient, with the sample thickness and sourced current as normalization factors.

This sequence command allows for a similar scheme, where the measurement is repeated across a user-defined range of applied field. The Initial and Final field values can be set, as well as the number of Steps to be sampled and the Spacing method to determine their distribution (linear, log(H), $H^2$, $H^{1/2}$, $H^{-1}$) throughout the range. An additional Settling parameter can be used to delay the execution of the measurement by the specified amount of time once the target field has been reached if desired.

Note that the resulting collection of data from this field scan are *not* further treated by the software- any additional fitting must be done in post-processing by the user.

### 3.3.4 Single Hall Effect

This command functions identically to that found in the associated Quick Measure dialog discussed in Section 3.2.4. The adjustment of the applied magnetic field must be handled using other sequence commands, and no IV curves are collected. Useful for troubleshooting and diagnostics or advanced seqeunce/macro design.

### 3.3.5 Single Resistivity

This command functions identically to that found in the associated Quick Measure dialog discussed in Section 3.2.3. No IV curves are collected. Useful for troubleshooting and diagnostics or advanced seqeunce/macro design.

## 3.4 File Structure

Executing a measurement, either via a sequence or using the Quick Measure dialogs, will generate a `.dat` file containing the relevant derived quantities calculated by the option software, and a `.raw` file which preserves all of the constituent individual voltage measurements for troubleshooting or manual calculations. If the user elects to collect IV curves (to verify contact health throughout the measurement) then a separate `.ivraw` file is also generated.

Each of these will share the same file name but are differentiated by their extensions. A listing of their contents is detailed in relevant sections which follow.

### 3.4.1 Measurement File Data Columns

**Table 3-7:** Data columns included in van der Pauw-Hall Option-produced `.dat` files.

| Field Name | Units | Description |
|---|---|---|
| Comment | | Text string included by the Datafile Comment command |
| Time Stamp | minutes, relative | When displayed as 'relative', the time dates from the creation of the data file; when displayed as 'absolute', the time is measured since the epoch of January 1, 1900. |
| Temperature | K | Active system/user temperature; recorded at the start of the measurement. |
| Magnetic Field | Oe | Applied DC magnetic field; recorded at the start of the measurement. |
| Position | deg. | If utilized in conjunction with the Horizontal Rotator option, the sample's angular orientation is reported here. |
| Measure ID | *count* | Each complete measurement of the resistivity or Hall coefficient receives a unique index. Starts at 1. |
| Ch.1/2/3 Resistivity | ohm-cm | Calculated volume resistivity; employs the user-supplied value for sample thickness. See Section 3.2.3 for details regarding the calculation. |
| Ch.1/2/3 Std. Err. | ohm-cm | Statistical standard error; takes the calculated standard deviation of the sampling of resistivity values and normalizes this by the square root of the number of readings. |
| Ch.1/2/3 Excitation | uA | User-specified excitation current. |
| Ch.1/2/3 Sheet Res. | ohms/Sq. | Calculated sheet resistance; independent of the user-supplied thickness parameter. See Section 3.2.3 for details regarding the calculation of resistivity, and Section 1.2.4.1 for information on its relation to sheet resistance. |
| Ch.1/2/3 IV | $R^2$ | The calculated coefficient of determination for a linear fit to the IV curve data. Supplied here as a proxy for linearity to aid the user in identifying / filtering measurements which were preceded by some non-ohmic behavior of the contacts. |
| Ch.1/2/3 Readings | *count* | User-specified number of voltage measures to average for each separate lead permutation employed by the measurement. |
| Ch.1/2/3 Config. | *code* | Refers to the number of voltages measured / averaged. See Table 3-9 for a full description. |
| Ch.1/2/3 Thickness | mm | User-specified sample thickness. |
| Ch.1/2/3 Status | *code* | A successful execution of the measurement routine always returns a value of zero. |

| Field Name | Units | Description |
|---|---|---|
| Ch.1/2/3 Hall Coeff. | ohm-cm/Oe | Calculated Hall coefficient; employs the user-supplied value for sample thickness. See Section 3.2.4 for details regarding the calculation. |
| Ch.1/2/3 Std. Err. | ohm-cm/Oe | Statistical standard error; takes the calculated standard deviation of the sampling of Hall coefficient values and normalizes this by the square root of the number of readings. |
| Ch.1/2/3 Excitation | uA | Excitation current sourced by the BRT module during the measurement. |
| Ch.1/2/3 Resistance | ohms | Ratio of the Hall voltage (averaged in various way based on the measurement configuration) to the excitation current . |
| Ch.1/2/3 Readings | | The user-specified number of readings averaged to produce the reported result. |
| Ch.1/2/3 Config. | *code* | Refers to the number of voltages measured/averaged. See Table 3-9 for a full description. |
| Ch.1/2/3 Thickness | mm | User-specified sample thickness. |
| Ch.1/2/3 Status | *code* | A successful execution of the measurement routine always returns a value of zero. |
| Ch.1/2/3 Carrier Density | $1/cm^3$ | Calculated carrier concentration; employs the user-supplied value for sample thickness via the Hall coefficient. See Section 1.3.1 for further discussion. |
| Ch.1/2/3 Mobility | $cm^2/V{\cdot}sec.$ | Calculated Hall mobility; independent of the user-supplied value for sample thickness. See Section 1.4 for further discussion. |
| Elapsed Time | sec | Time elapsed between the start of the first reading to the completion of the last reading. |
| Min. Temperature | K | Minimum temperature recorded during the measurement; 1 second sampling interval. |
| Max. Temperature | K | Maximum temperature recorded during the measurement; 1 second sampling interval. |
| System Temperature | K | Nominal PPMS temperature; when using the Horizontal Rotator option this is different from the temperature reported by the rotator thermometry. Recorded at the start of the measurement. |
| Pressure | torr | Reported PPMS sample chamber pressure at the start of the measurement. |
| Temperature Status | *code* | Reported PPMS temperature status code at the start of the measurement. |
| Magnet Status | *code* | Reported PPMS temperature status code at the start of the measurement. |

| Field Name | Units | Description |
|---|---|---|
| Chamber Status | *code* | Reported PPMS magnet status code at the start of the measurement. |

## 3.4.2 Raw File Data Columns

The van der Pauw - Hall Option potentially outputs two separate files containing raw or unprocessed data. The first of which is the `.raw` file, which records each individual voltage measurement used in the process of calculating the van der Pauw resistivity and Hall coefficient values.

**Table 3-8:** Data columns included in van der Pauw-Hall Option-produced `.raw` files.

| Field Name | Units | Description |
|---|---|---|
| ASB State | *code/comment* | Comments provide information about the measurement which follows (which channel, when measurements were executed). Code indicates the switching state of the ASB; see Table C- 2 Section C.3 for a complete description. |
| Time Stamp | minutes/seconds, relative/absolute | When displayed as 'relative', the time dates from the creation of the data file; when displayed as 'absolute', the time is measured since the epoch of January 1, 1900. |
| Measure ID | *count* | Each complete measurement of the resistivity or Hall coefficient receives a unique index; individual voltage measures used in the calculation of the result share the same Measure ID value. Starts at 1. |
| Channel | - | Indicates which bridge channel the individual measure was executed on. If multiple channels are selected for a given measure (i.e.: vdP resistivity, Hall) they will share a Measure ID. |
| VdP/Hall | *code* | Indicates the type of measurement being executed; either (1) for a van der Pauw resistivity type, or (2) for the transverse voltage / Hall coefficient. |
| Config | *code* | Refers to the user-selected measurement configuration; the code itself is a proxy for the number of voltages measured/averaged. See Table 3-9 for a full description. |
| Switch | *code* | Indicates the precise switching state of the ASB hardware. The numeric labels here map to the associated diagram and table entry as given in Section C.3. |
| Readings | *count* | User-specified number of voltage measures to average for each separate lead permutation employed by the measurement. |
| R | Ohms | Applying Ohm's law, the simple ratio between the sourced excitation ('Drive', see below) and the measured voltage response ('Volts', see below). |

| Field Name | Units | Description |
|---|---|---|
| R.Std.Err. | Ohms | Statistical [standard error](#); takes the calculated standard deviation of the sampling of resistance values and normalizes this by the square root of the number of readings. |
| Drive | uA | The user-specified excitation sourced to the sample. |
| Volts | uV | The measured voltage response from the sample. |
| Elapsed Time | sec | Time elapsed between the start of the first reading to the completion of the last reading. |
| Temperature | K | Nominal PPMS temperature; when using the Horizontal Rotator option this is different from the temperature reported by the rotator thermometry. Recorded at the start of the measurement. |
| Magnetic Field | Oe | Applied DC magnetic field; recorded at the start of the measurement. |
| Position | deg | If utilized in conjunction with the Horizontal Rotator option, the sample's angular orientation is reported here. |
| Status | code | A successful execution of the measurement routine always returns a value of zero. |
| Volts+ | uV | The recorded voltage observed under nominal current flow. |
| Volts- | uV | The recorded voltage observed under reversed-polarity current flow. |

### 3.4.2.1 'Config' Codes

**Table 3-9:** Config parameter code explanations. See SECTION IN SOFTWARE for a complete explanation of the motivation to choose which one...

| Config Code | vdP/Hall Code | Description | Voltages Averaged | Switch Positions |
|---|---|---|---|---|
| 2 | 1 | vdP (classic) | 2 | 2 |
| 2 | 2 | Hall (quick) | 2 | 1 |
| 4 | 1 | vdP (quick) | 4 | 2 |
| 4 | 2 | Hall (RMFR) | 4 | 2 |
| 8 | 1 | vdP(average) | 8 | 4 |
| 8 | 2 | Hall (average) | 8 | 4 |

## 3.4.3  IV Raw File Data Columns

The van der Pauw - Hall Option potentially outputs two separate files containing raw or unprocessed data. The second of which is the `.ivraw` file, which records, if requested by the user, each individual current/voltage

measurement comprising an IV curve. IV curves are associated with a Measurement ID, allowing the user to quickly determine in troubleshooting questionable values from the `.dat` file if these can be correlated with non-linear IV curves. Extracted data associated with poor R-squared values should generally be disregarded.

**Table 3-10:** Data columns included in van der Pauw-Hall Option-produced `.dat` files.

| Field Name | Units | Description |
|---|---|---|
| Time Stamp | minutes, relative | When displayed as 'relative', the time dates from the creation of the data file; when displayed as 'absolute', the time is measured since the epoch of January 1, 1900. |
| Measure ID | *count* | Indicates which measurement from the `.dat` file the IV datum corresponds to; each complete measurement of the resistivity or Hall coefficient receives a unique index. Individual IV point measures of a single curve share the same Measure ID value. Starts at 1. |
| Channel | - | Indicates which bridge channel the individual measure was executed on. |
| Current | uA | Excitation current; independent variable parameter of the IV curve. |
| Voltage1/2/3 | uV | Detected voltage response of the sample. |
| R-squared | - | The calculated coefficient of determination for a linear fit to the IV curve data. Supplied here as a proxy for linearity to aid the user in identifying/filtering measurements which were preceded by some non-ohmic behavior of the contacts. |

# van der Pauw-Hall Measurements

## 4.1   Measurement Procedures

Measurements using the van der Pauw - Hall Option entail mounting the sample to the Resistivity puck and properly inserting the switch box in-line with the measurement circuit. From there, the option software measurement commands can be easily included in sequences to automate data collection.

### 4.1.1   Sample Preparation

When considering a sample for measurement, keep in mind the requisite criteria (listed in Section 1.2.3.1) that must be satisfied for the van der Pauw relation to be applicable. Samples which might not strictly conform to these requirements (thicker samples, relatively large contacts, etc.) can still be measured, but accuracy may potentially suffer. A thorough literature search is recommended for such cases to attempt to quantify any systematic errors.

#### 4.1.1.1 Preparing the Puck

The Resistivity puck has a large, open, square-shaped region for affixing samples. This part of the puck is composed of gold-plated copper to aid in thermal conduction, but is also electrically connected to the sample chamber walls and in turn the PPMS ground. For these reasons, it's recommended to prepare the puck by attaching an electrically insulating barrier between the puck base and the sample.

A common choice is an appropriately sized square of thin cigarette paper. This paper is readily sourced and is thin enough that it can electrically insulate the sample without isolating it thermally. An appropriate adhesive (VGE-7031 varnish is recommended[1]) can be thinned down, and the paper soaked in the dilute adhesive before affixing it to the puck. When the adhesive has set, the puck now has a semi-permanent barrier to avoid electrical shorts to the puck, which is important for collecting quality electrical transport data. Note that over time, the paper will degrade, and it should be replaced from time to time, so the user of permanent adhesives (i.e.: epoxy) is not recommended.

#### 4.1.1.2 Mounting the Sample

The same VGE-7031 is recommended to adhere the sample to the paper barrier on the puck. It is not suggested to use any more adhesive than is necessary to mechanically secure the sample. By minimizing the thermal barrier between the puck's gold-plated surface and the sample, the varnish will aid somewhat in thermal equilibration of the sample with the puck; an excess of varnish can actually impede this process, so a sparing quantity is recommended. Barring some special circumstance, transport measurements are also usually run in the presence of helium exchange gas, which further aids in equilibration between the sample and the puck/chamber.

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[1] VGE-7031 is an electrical insulator and has better-than-average thermal conductance in cryogenic environments compared with many other comparable adhesives. It sets rigidly, but can also be fairly easily removed by dissolution via the proper solvent.

### 4.1.1.3 Attaching Leads

There are many ways to attach wires to samples, and a detailed discussion of each is beyond the purview of this manual. Common techniques include silver paint, silver epoxy, wire bonding, and spot welding. The wires chosen should have reasonably high conductivity (i.e.: gold, silver, copper, related alloys, etc.) and be sized such that appropriately small contacts can be made at the sample.[2]

Once the wires are connected to the sample, they should be attached to the contact pads of one of the channels of the Resistivity puck as indicated in Figure 4-1. Regardless the shape of the sample, or where the contacts are placed, the contacts must be wired such that their order, starting from the positive current lead and moving *clockwise* around the sample perimeter, is: $+I \Rightarrow -I \Rightarrow -V \Rightarrow +V$.

This relative positioning is crucial, as the automated voltage measurement averaging makes assumptions about the nominal lead configuration so that it can handle subsequent permutations thereof to appropriately quantify the property of interest. Contacts cannot be arbitrarily mapped later in software, so this step is important.
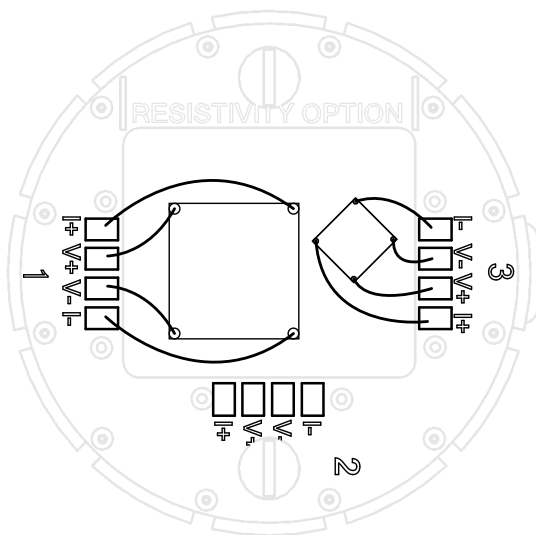


**Figure 4-1:** Sample wiring diagram for all samples using the van der Pauw - Hall option's automated measurement commands. Despite different sizes and orientations, both samples follow the clockwise scheme described in the text.

One important note: measurements of sample resistivity and Hall coefficient for the purposes of calculating carrier mobility are often of greatest interest for semiconducting samples. Generally, it is non-trivial to create proper ohmic contacts with many semiconducting materials. The user is encouraged to utilize the IV Curve utility in MultiVu (described in Section 3.2.5) to verify ohmic contacts upon installation of the sample to help assure accurate measures of the van der Pauw resistivity and Hall coefficient.

## 4.1.2  Configuring Measurement Hardware

### 4.1.2.1 Install Electronics

Confirm that the BRT is already installed in a CAN bay; if it is not, refer to Section A.1.3 for further instructions.

Next, check that the switch box USB cable is directly connected to the MultiVu PC (not via a USB hub, as this can cause serial communication problems), and that it is powered with the included AC adapter. Turn the rocker switch on the back to the 'on' position to power the switching relays. At this point all three of the 'Status' indicators should display green.

### 4.1.2.2 Cabling

Connect one User Bridge cable to the 14-pin LEMO socket on the PPMS cryostat, and the other end to the DB-25 labeled 'Output' on the switch box. A second User Bridge cable connects at the 14-pin LEMO 'Input' connector of

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[2] Further questions concerning the specifics of sample mounting should be sent to apps@qdusa.com.

the switch box, with its DB-25 end mating to the JL-1 'Bridge' port of the BRT module. A connection diagram is shown in Figure 4-2. Secure the screws of the two DB-25 connectors to ensure a solid connection.
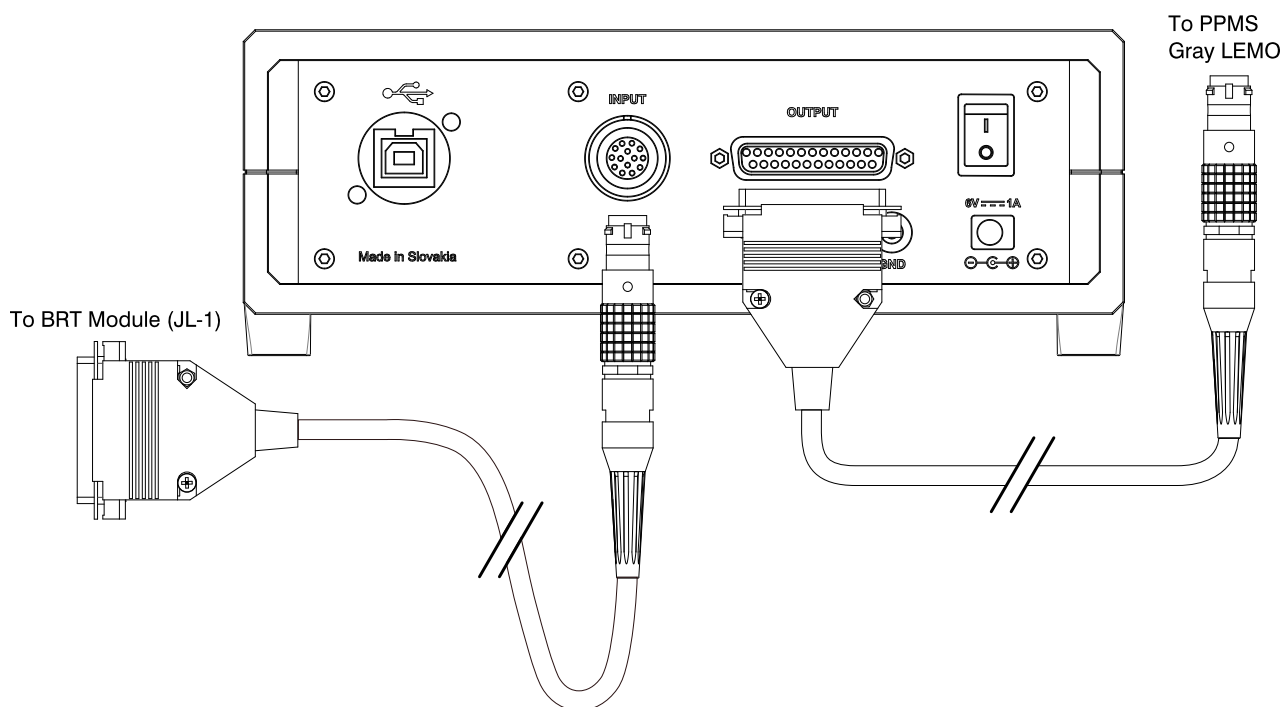


**Figure 4-2:** Connection diagram indicating how to interface the switching box with the BRT module and the PPMS sample chamber connector. The cables shown are interchangeable, and wired identically to the LEMO cable used with the Resistivity Option (QD part no. 3084-005-01/-02).

### 4.1.2.3 Initiate Communication

Active the van der Pauw - Hall Option software (**Utilities>Activate Option…**) within MultiVu. If there is an issue with the serial communication with the switch box, the software will report an error here. See Section B.1 for more information on resolving this problem.

## 4.1.3   Installing the Sample

First ensure the PPMS sample chamber has settled at 300 K and that the magnetic field has been ramped down to zero. A simple wizard can then be triggered via the **Install**/**Remove...** button which will automate the sample space venting and prompt the user to install the sample before executing the purge/seal operation. It is recommended that the baffle set included with the PPMS be installed here as well to ensure access to the full temperature range of the instrument.

Once the sample is installed, as mentioned prior, it is strongly suggested that the sample contacts are tested with the IV Curve utility to verify an ohmic response. If these curves are nonlinear, additional work in preparing the contacts is required before accurate resistivity or Hall measurements can be made. Alternatively, excitations may be limited exclusively to the ohmic region of the response, but note that the extents of this region can evolve with temperature.

The same caveat applies even for samples with well-behaved ohmic contacts at room temperature; for this reason the measurements where the user elects to collect IV curves beforehand also include the associated $R^2$ value reported in the `.dat` file. This value acts as a proxy for IV curve linearity, and can be used as a diagnostic tool to troubleshoot unexpected behavior in the transport properties arising from a nonlinear response of the contacts.

### 4.1.4    Sample Measurement

At this point, if the quality of the contacts is satisfactory, the user can proceed to run an immediate measurement at room temperature to make an assessment of the appropriate excitation at which to collect the desired data. With that decided, it should be straightforward to build up and execute a sequence to measure the van der Pauw resistivity, the Hall coefficient, or the combined carrier mobility as desired.

Details regarding the settings of these measurement commands are provided in complete detail in Chapter 3.

## 4.2    Removing the van der Pauw - Hall Option

When the experiment is over, set the magnetic field to zero and the system temperature to 300 K. When the field has ramped down and the temperature is stable, the sample chamber can be vented. Remove the baffle set.[3] Use the puck extraction tool to remove the resistivity puck; cap the chamber and use the **Chamber Operations** menu to **Purge**/**Seal** the sample space.

The LEMO cable connecting the PPMS to the switching box, as well as the cable connecting the switching box to the BRT Module, can be removed and stored together. The power to the switching box should be turned off, but the other connections (power, USB communication) can be left plugged in with the box in the idle state.

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[3] If the baffle set is still cold from a fast warm-up, water vapor from the air may accumulate as frost; in this case set it aside to warm to room temperature, and dry thoroughly before reinstalling in the sample space.

# Auxiliary Operation

The van der Pauw - Hall option is an enhancement to the existing DC Resistivity option, which is itself compatible with a number of other options provided by Quantum Design. As such, the VDPH option's functionality extends to those situations as well. Updated connection diagrams and comments on usage with these options are provided in the following sections.
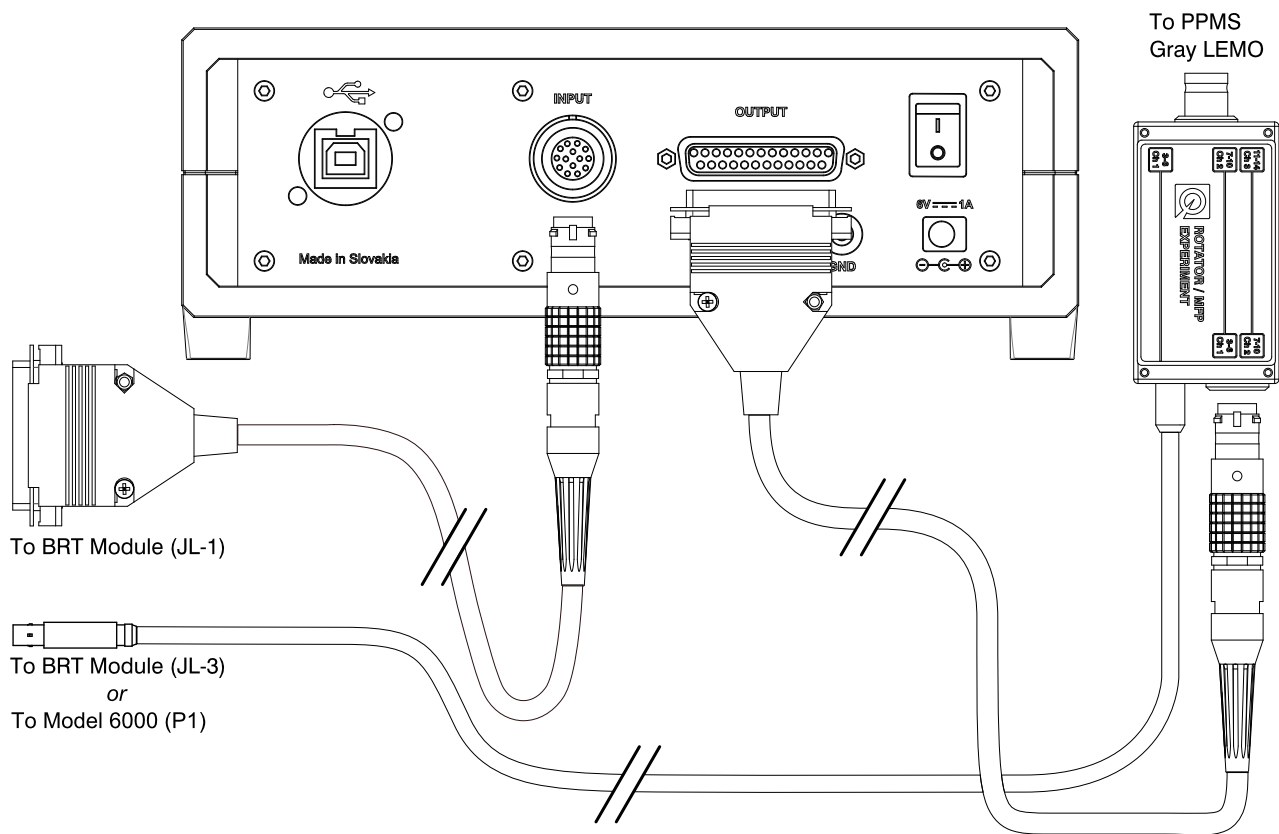
## 5.1 Horizontal Rotator

The horizontal rotator enables the *in situ* rotation of a sample with respect the applied magnetic field. Combining this with the van der Pauw method for determining sample resistivity, and the large applied magnetic field available in the PPMS, allows for the angular dependance of a sample's magnetoresistance to be accurately determined.

Due to the additional thermal mass from the rotator insert, local thermometry at the sample has been integrated into the probe. This thermometer, measured by the BRT module, occupies four of the twelve available connections in the PPMS sample space; as such, the rotator sample boards have only enough leads to accommodate two 4-probe measurements instead of three for the standard Resistivity puck. The channels on the board utilize the same current/voltage layout as the standard puck, so samples are identically as described in Section 4.1.1.3.

Since the Ch. 1 wiring is being used by the rotator thermometer, the sample board channels are labeled as Ch. 2 and Ch. 3. The Rotator/MFP patch box, included with the option, re-routes these wires where they take the positions of Ch. 1 and Ch. 2 on a pass-through LEMO socket (see the patch box details in Figure 5-1). As such, the sample wired to Ch. 2 *on the sample board* will be measured by the option software at Ch. 1, and the sample wired to Ch. 3 *on the sample board* will be measured by the option software at Ch. 2.

Keep a careful eye on the rotator thermometry- cooling power is more limited when using the rotator, so sample self-heating can more easily destabilize the temperature. Consider running a few trials at base to determine the lowest excitation which still produces satisfactory signal-to-noise to avoid this issue. Note as well that quickly ramping the field back and forth for repeated mobility measurements can induce eddy currents in the probe, which can also destabilize the temperature. To mitigate this problem, it may be necessary to measure the resistivity and Hall coefficient on separate sweeps, to avoid using excessive time waiting for thermal stability between field ramps, and calculate the mobility manually.

A complete connection diagram follows in Figure 5-1

**Figure 5-1:** Connection diagram indicating how to interface the switching box with the BRT module and the PPMS sample chamber when utilizing the horizontal rotator. The LEMO/DB-25 cables shown are interchangeable, and wired identically to the LEMO cable used with the Resistivity Option (QD part no. 3084-005-01/-02). The Rotator/MFP patch box (QD part no. 3084-010-01/02) routes the rotator thermometry to the BRT, and rewires the remaining measurement channels to the Ch. 1 / Ch. 2 positions on the pass-thru LEMO socket.

# 5.2   Helium-3 Refrigerator

The Helium-3 refrigerator enables measurements from 350 K down to 400 mK, extending the base temperature of the standard PPMS and DynaCool instruments.

Due to the additional thermal mass from the Helium-3 insert, local thermometry at the sample has been integrated into the probe. This thermometer, measured by the He-3 control module, occupies four of the twelve available connections in the PPMS sample space; as such, the Helium-3 sample boards have only enough leads to accommodate two 4-probe measurements instead of three for the standard Resistivity puck. The channels on the board utilize the same current/voltage layout as the standard puck, so samples are identically as described in Section 4.1.1.3.

Ch. 3 wiring is used to measure the control feedback thermometer on the sample stage, so the sample board channels are labeled as Ch. 1 and Ch. 2. The Helium-3 patch box, included with the option, simply passes these connections through to a LEMO socket to plug the standard Resistivity LEMO cable into. Channel labeling on the sample board corresponds to that of the option software.

Keep a careful eye on the Helium-3 thermometry- cooling power is far more limited near the base of 400 mK, so sample self-heating can more easily destabilize the temperature. Consider running a few trials at base to determine the lowest excitation which still produces satisfactory signal-to-noise to avoid this issue. Note as well that quickly ramping the field back and forth for repeated mobility measurements can induce eddy currents in the probe, which can also destabilize the temperature. To mitigate this problem, it may be necessary to measure the resistivity and

Hall coefficient on separate sweeps, to avoid using excessive time waiting for thermal stability between field ramps, and calculate the mobility manually.

A complete connection diagram follows in Figure 5-2.
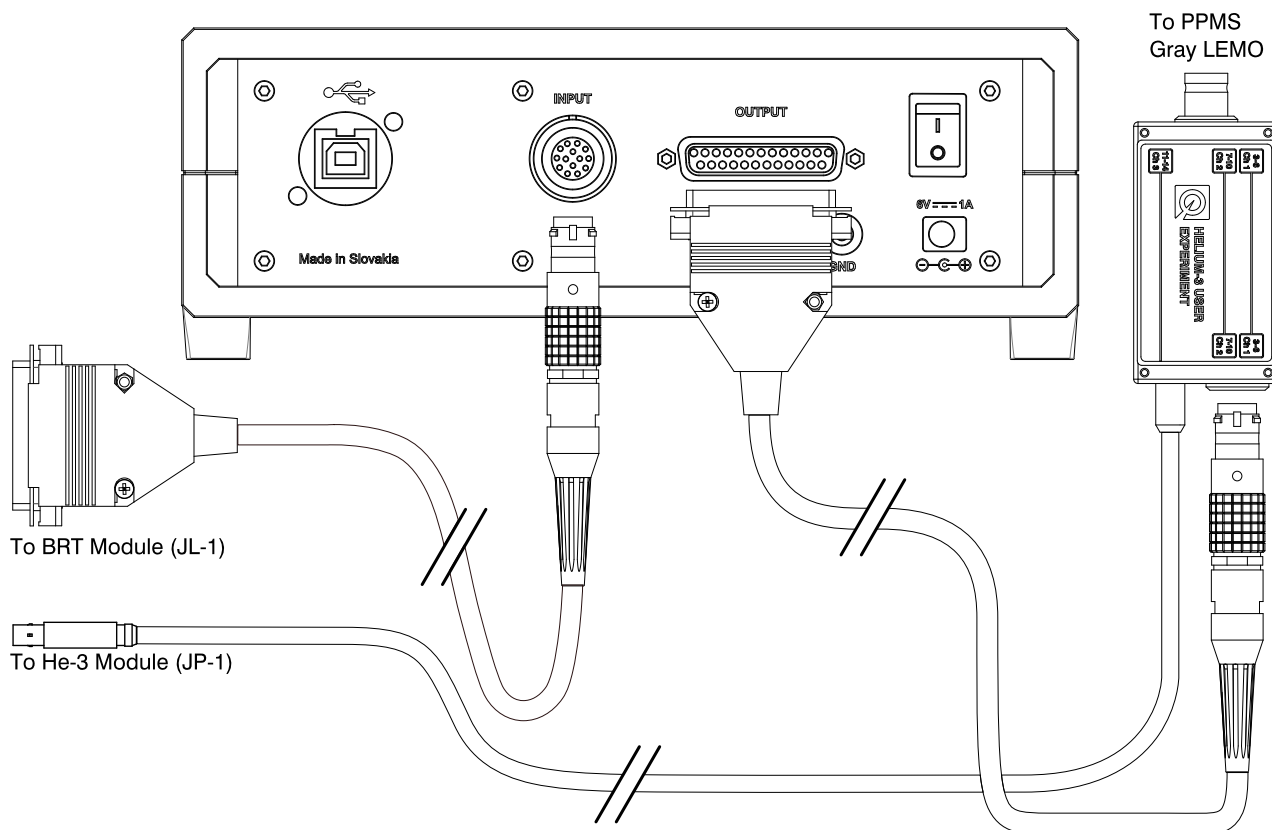


**Figure 5-2:** Connection diagram indicating how to interface the switching box with the BRT module and the PPMS sample chamber when utilizing the Helium-3 refrigerator. The LEMO/DB-25 cables shown are interchangeable, and wired identically to the LEMO cable used with the Resistivity Option (QD part no. 3084-005-01/-02). The Helium-3 patch box (QD part no. 3092-359-01/02) routes the Helium-3 insert thermometry to the He-3 control module and the Ch. 1 / Ch. 2 wiring to the pass-thru LEMO socket.

## 5.3    Dilution Refrigerator

The dilution refrigerator enables measurements from 4 K down to 50 mK, extending the base temperature of the standard PPMS and DynaCool instruments.

Due to the additional thermal mass from the DR insert, local thermometry at the sample has been integrated into the probe. This thermometer, among others used to properly manage the refrigeration cycle, are measured by the DR control module utilizing their own dedicated wiring. Eight conductors of auxiliary wiring are available for sample measurements and these utilize a separate connector on the neck of the DR.

As such, the DR sample boards have only enough leads to accommodate two 4-probe measurements instead of three for the standard Resistivity puck. The channels on the board utilize the same current/voltage layout as the standard puck, so samples are identically as described in Section 4.1.1.3. The sample board channels are labeled as Ch. 1 and Ch. 2, and the cabling is wired such that these labels correction corresponds to identical channels in the option software.

Keep a careful eye on the DR thermometry- cooling power is far more limited near the base of 50 mK, so sample self-heating can more easily destabilize the temperature. Consider running a few trials at base to determine the lowest excitation which still produces satisfactory signal-to-noise to avoid this issue. Note as well that quickly

ramping the field back and forth for repeated mobility measurements can induce eddy currents in the probe, which can also destabilize the temperature. To mitigate this problem, it may be necessary to measure the resistivity and Hall coefficient on separate sweeps, to avoid using excessive time waiting for thermal stability between field ramps, and calculate the mobility manually.

A complete connection diagram follows in Figure 5-3.
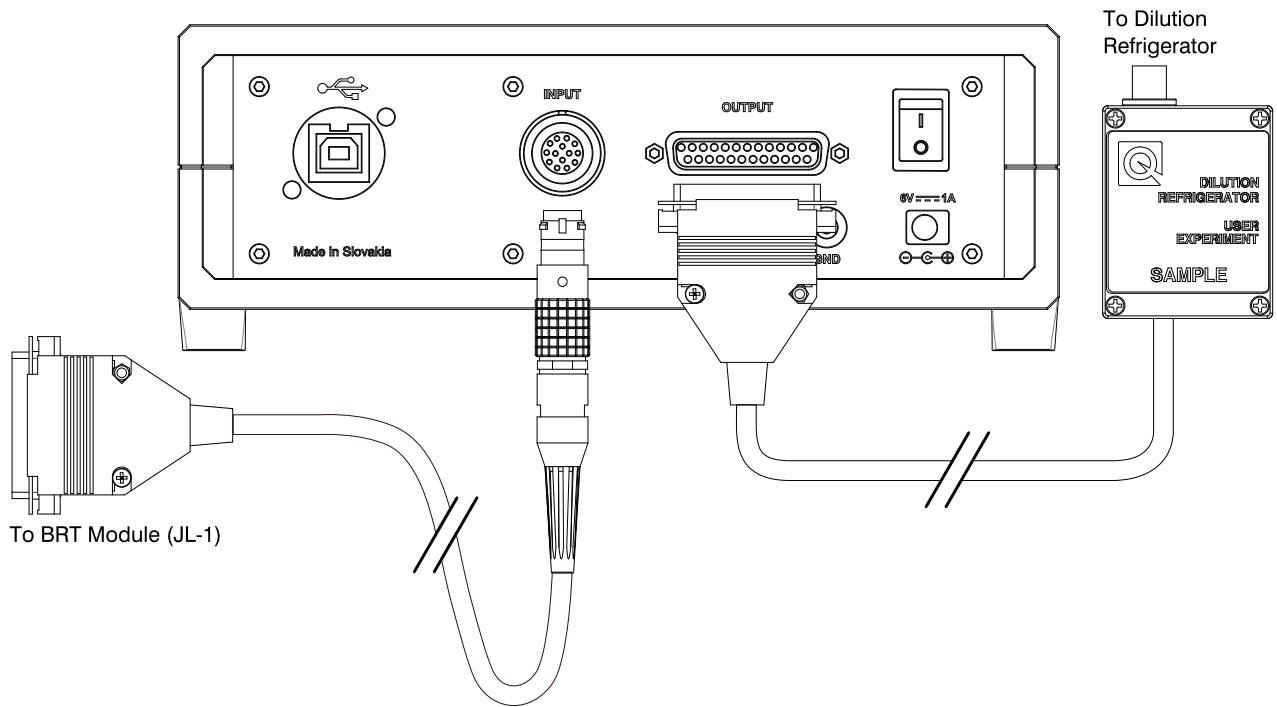


**Figure 5-3:** Connection diagram indicating how to interface the switching box with the BRT module and the dilution refrigerator sample stage. The LEMO/DB-25 cable is wired identically to the cable used with the Resistivity Option (QD part no. 3084-005-01/-02). The DR RF filter box (QD part no. 3091-630) routes the Ch. 1 / Ch. 2 wiring to switch box.

**CHAPTER 6**

# Maintenance

## 6.1 Cleaning Hardware

### 6.1.1 Resistivity Puck

#### 6.1.1.1 Chassis

The gold-plated metal chassis of the puck can be readily cleaned of adhesives and grease using mild organic solvents such as acetone or isopropyl alcohol. Avoid submerging the puck fulling in a bath of solvent for any extended period of time, as other components can be damaged with prolonged exposure.

#### 6.1.1.2 Printed Circuit Board

The PCB component of the puck can also be spot-cleaned with mild organic solvents. From time to time it is also advised to clean the pads and add fresh solder. As oxides accumulate on the surface of the solder beads, a thermal barrier can develop requiring an excessively hot iron to melt the solder. This in turn causes a large thermal stress on the PCB, which will significantly accelerate its degradation and artificially shorten the lifetime of the puck.

# APPENDIX A

# Initial Installation

## A.1 Use of This Guide

If the van der Pauw-Hall Option has never been used, the following sections will guide the user through the process of the initial setup. These steps in are only intended to describe the installation of the vdP-Hall Option for the first time. Part or all of this procedure may have been completed already if the option shipped with the base system from Quantum Design. In this case, or once the initial user installation has been completed, the option is simply activated when needed, as described in Section 4.1.

### A.1.1 Prerequisites

The vdP-Hall Option is compatible with the DynaCool, PPMS (with or without EverCool II), and VersaLab. Beyond a compatible base system, a few extra components are necessary for successful installation and operation:

- BRT CAN Module

- Model 1000 tower (for PPMS base systems)

- MultiVu software

If some of these items still need to be installed, refer to their corresponding manuals and complete the installations. If any of these items are missing or not working properly, contact service@qdusa.com to resolve the issue before proceeding with the vdP-Hall Option installation.

### A.1.2 Option Software Installation

Before continuing, it is also a good idea to ensure that the base installation of MultiVu is up-to-date with the current version. This software can be found under either the DynaCool or PPMS sections of the 'Software Upgrades' section of the Quantum Design website.

Once the MultiVu installation is current, option software can also be downloaded from the same page. With MultiVu closed, run the installation wizard for the vdP-Hall Option.

#### A.1.2.1 Identifying the COM Port

When the installation is complete, browse to the root folder of the instrument (usually `C:\QdPpms` or `C:\QdDynacool`) and find the `\vanderPauwHall\System` directory. Inside, open the `vanderPuawHall.ini` file and make a note of the value assigned to `Port`.

In Windows, open the Device Manager console. Expand the list titled **Ports (COM & LPT)** and look for an item titled **USB Serial Device**. A COM port (i.e.: COM2, COM5, etc.) will be listed beside this. Make sure it matches the value in the `.ini` file. If it does not, update the `.ini` file to match the port listed in Device Manager and save the changes.

If more than one device is listed, unplug the other peripheral to isolate which one corresponds specifically to the switching box. The other devices can be reconnected afterward.

When these steps are complete, proceed to installing the BRT Module.

### A.1.3 Installing the BRT CAN Module

The BRT CAN Module may already be installed. If it is not, proceed as follows. First verify that all of the items on the Key Components list (near the start of this manual) were included with the van der Pauw-Hall Option and that they appear undamaged. If everything is in order, continue on to installing the BRT Module.

a. Ensure that all options have been deactivated in MultiVu.

b. Power down the CAN rack (DynaCool) or the Model 1000 (PPMS). For the VersaLab, the full system will need to temporarily be powered off using the main switch on the back of the instrument.

> **Warning:** Never install or remove a CAN module while the module bay is still powered. This can permanently damage the electronics.

c. Identify an empty module bay and remove the cover plate; if all bays are full, remove a module that will not be need.

d. Insert the BRT Module into the empty bay (PPMS/Model 1000 Note: the module is keyed for the 'low-power' style bays and will fit in any open slot of the Model 1000). Secure the module in place with the integrated thumb-screws.

e. Re-power the CAN bay.

### A.1.4 Confirm Option Activation

With the software and electronics installed and the correct configuration file in place, the system is ready to be activated for the first time:

a. Open the **Utilities>Activate Option** menu in MultiVu to bring up the Option Manager

b. Select the **van der Pauw-Hall** item and click **Activate**.

c. Check the van der Pauw-Hall Log window to confirm communication has been established with the BRT Module.

d. The van der Pauw-Hall Option is now properly configured. The option software can be deactivated if a measurement will not be conducted right away. If the user is ready for a measurement, proceed to Chapter 4.

# A.2 Subsequent Installations

If the steps comprising the initial installation are already complete, refer to Section 4.1 for details outlining a typical activation of the vdP-Hall Option once installed.

# Troubleshooting

## B.1 COM Port Error

Communication with the ASB102 is facilitated via serial communication over a USB cable. To the PPMS control PC, the ASB micro-controller hardware presents itself as a COM device. It is important that when the van der Pauw-Hall option software is initialized it knows which COM port to use in order to relay the switching instructions.

If the configuration specifies the wrong COM port, or the USB cable is not connected, the software will return an error similar to the one shown in Figure B-1.
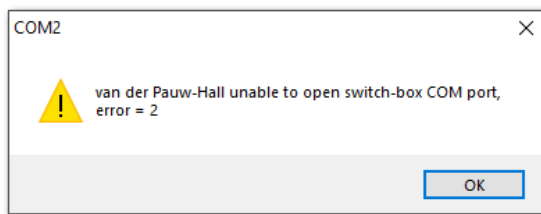


**Figure B-1:** An example of the error message returned by the option software when no ASB hardware is found at the specified COM port.

### B.1.1 Recommended Action

Refer to Section A.1.2.1 for instructions to identify the correct COM port and update the `.ini` file if needed.

## B.2 Switches Don't Actuate During Measurements

If the software successfully activates, but upon running measurements the lights on the front panel of the ASB102 do not change, and no audible 'clicking' is heard, this can indicate a communication issue between the hardware and the VDPH software.

This can occur when the COM port specified in the `.ini` file is occupied by a device *other than the ASB102*. Since there is a device present, no error is thrown, but the ASB102 is 'listening' on a different port, so it never receives the instructions sent by the software to actuate the internal switches.

### B.2.1 Recommended Action

Refer to Section A.1.2.1 for instructions to identify the correct COM port and update the `.ini` file if needed.

## B.3 Negative Resistance

One of the most common issues encountered in basic transport measurements is the instrumentation reporting a resistance with a negative sign. While technically possible for some nonlinear systems, clearly such a result is non-physical for hardware designed to operate on samples and devices obeying Ohm's Law.

It's worth noting here that most transport measurements are based on this assumption of ohmic behavior. As such, the electronics will always blindly evaluate the ratio of detected (sourced) voltage to the sourced (detected) current to arrive at a value resistance.

*Possible Cause: Leads Miswired*

The easiest way to generate a result with the incorrect sign is to accidentally permute the +/- sense of one set of leads. Doing so ensures that the sign of the measured potential drop is now *opposite* that of the sourced current . This is an easy issue to resolve and avoid in the future. In the case of the van der Pauw - Hall option, please carefully consult the notes and diagrams in Section 4.1.1.3

*Possible Cause: Open Circuit*

The other culprit which can regularly generate negative resistances is an unplugged cable. The software doesn't necessarily know the current source is in a compliance state (i.e.: having insufficient voltage to sustain the requested current flow), so it still records the voltage and computes the ratio. Whether owing to a broken lead or an unplugged cable, any detected voltage is simply noise, which generally takes a negative sign as often as a positive one.

In this case, the reported resistance will often be quite unstable, exhibiting large swings in magnitude as well as sign. Visually inspect cabling and leads to verify the continuity path; confirm using a multimeter if necessary.

## B.3.1 Recommended Action

While issues can always arise during an extended measurement, many of these problems are easily caught using the IV curve utility described in Section 3.2.5 before starting a sequence. For further questions concerning sample mounting please reach out to apps@qdusa.com.

# Wiring Information

## C.1    Resistivity Puck

The resistivity puck is wired to access all 12 connections available in the PPMS sample chamber. When installed in the chamber, these are accessed via the standard 14-pin LEMO connector. The connection numbering scheme is based off the 14-pin LEMO connector, where pins 1 and 2 are unused. Hence, the 12 connections available at the puck are numbers 3 through 14. The spatial positions of these connections are shown below in Figure C-1. Their relation to the labeled pads on the top side of the puck is given in Table C-1.
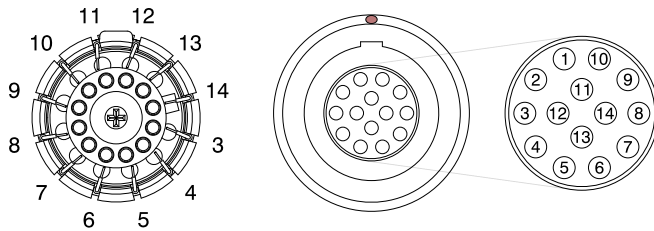


**Figure C-1:** Connection labels for the resistivity puck and the 14-pin LEMO socket. *Note:* the LEMO connector is shown as seen from the user's perspective (*not* the back side to which the chamber wiring is soldered).

## C.2    User Bridge LEMO Cable

The connection labels for the User Bridge cable[1] normally used to connect the PPMS to the BRT module are given in Figure C-2. The van der Pauw-Hall Option uses two of these cables: one connects the PPMS to the switching box, and one connects the switching box to the BRT Module (see Figure 4-2). The DB-25 pins' correspondence to the sample chamber and puck wiring are given in Table C-1.
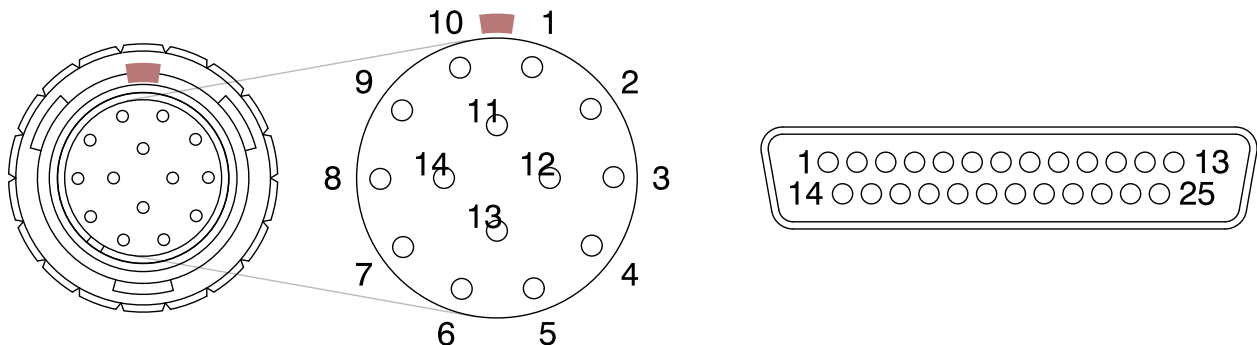


**Figure C-2:** Connection labels for the User Bridge cable (QD part No.s 3101-456-(01,02). At left, the 14-pin LEMO plug ('key' shaded), at right the DB-25 connector. *Note:* both connectors are shown as seen from the user's perspective (*not* the back side to which the wires are soldered).

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[1] Also referred to as the Resistivity Option cable.

| Sample Puck | 14-Pin LEMO | DB-25 Connector | Description |
|---|---|---|---|
|  | 1 |  | (Unused) |
|  | 2 |  | (Unused) |
| 3 | 3 | 5 | Channel 1 I+ |
| 4 | 4 | 15 | Channel 1 I - |
| 5 | 5 | 6 | Channel 1 V+ |
| 6 | 6 | 19 | Channel 1 V- |
| 7 | 7 | 7 | Channel 2 I+ |
| 8 | 8 | 20 | Channel 2 I - |
| 9 | 9 | 8 | Channel 2 V+ |
| 10 | 10 | 21 | Channel 2 V- |
| 11 | 11 | 9 | Channel 3 I+ |
| 12 | 12 | 22 | Channel 3 I - |
| 13 | 13 | 10 | Channel 3 V+ |
| 14 | 14 | 23 | Channel 3 V- |
|  |  | 13 | Cable shielding[2] |

# C.3   vdP-Hall Switch Box

Given the switching box's ability to permute its configuration, a traditional diagram or table (or many of them) describing the connection routing is not especially 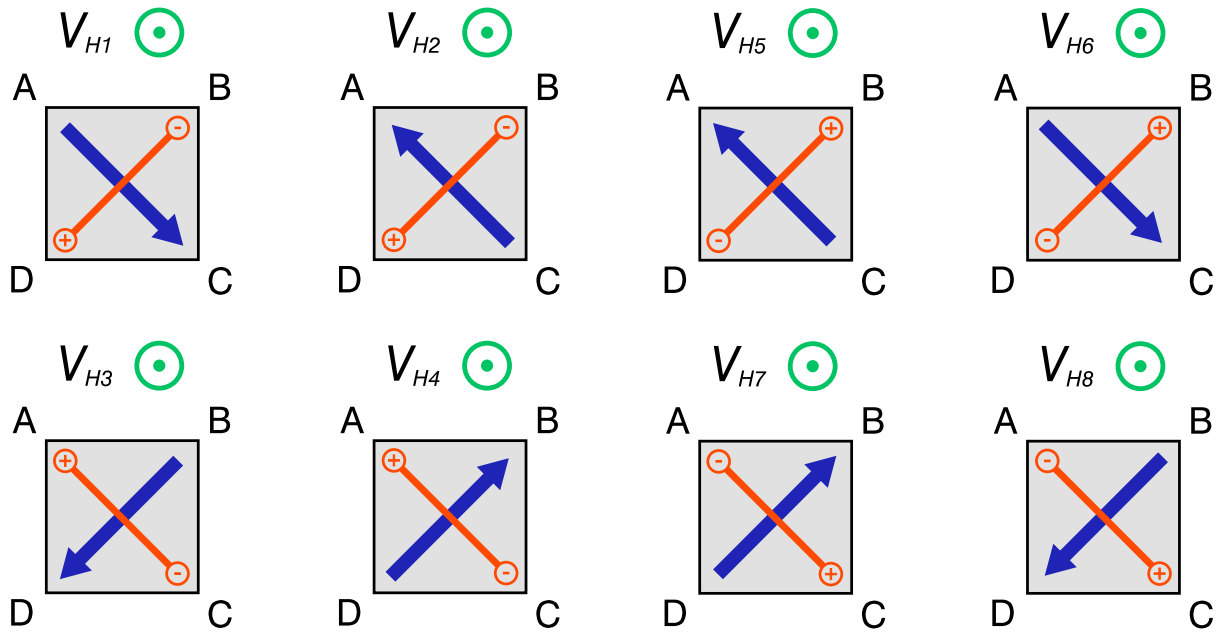helpful. Instead, here convention used throughout this manual and in the software is presented in its entirety, beginning with the labels of the voltages for all eight available configurations for a van der Pauw resistivity measurement, shown in Figure C-3. A similar set of permutations exists for the Hall configuration, the eight unique permutations of which are shown in Figure C-4.

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[2] This shielding is comprised of a metalized wrapper around the conductor bundle of the cable. It is not electrically connected to anything at the LEMO side of the cable to prevent grounding loops.

$V_1$

A — B
D — C

$V_2$

A — B
D — C

$V_5$

A — B
D — C

$V_6$

A — B
D — C

$V_3$

A — B
D — C

$V_4$

A — B
D — C

$V_7$

A — B
D — C

$V_8$

A — B
D — C
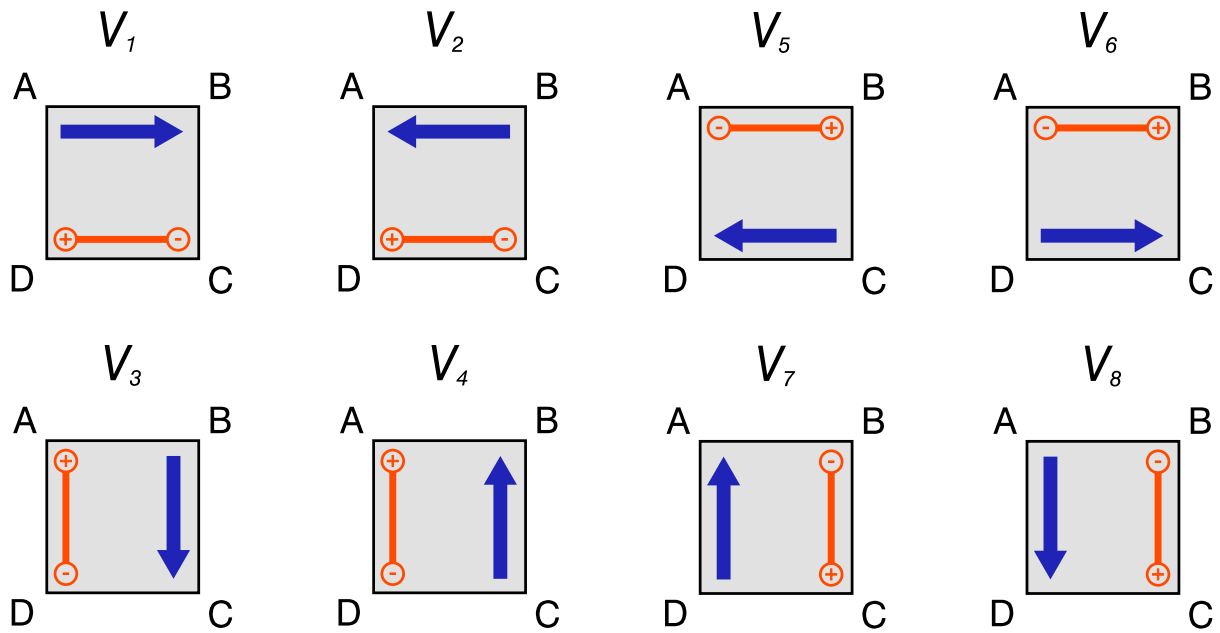
**Figure C-3:** Notational convention for van der Pauw resistivity voltage measurements. The subscripts are referenced elsewhere as the 'voltage index'.

$V_{H1}$ ⊙

A — B
D — C

$V_{H2}$ ⊙

A — B
D — C

$V_{H5}$ ⊙

A — B
D — C

$V_{H6}$ ⊙

A — B
D — C

$V_{H3}$ ⊙

A — B
D — C

$V_{H4}$ ⊙

A — B
D — C

$V_{H7}$ ⊙

A — B
D — C

$V_{H8}$ ⊙

A — B
D — C

**Figure C-4:** Notational convention for Hall voltage measurements. The subscripts are referenced elsewhere as the 'voltage index'.

Samples should be wired such that the contact labels A, B, C, D correspond to resistivity puck contact pad labels of +I, -I, -V, +V (see Figure 4-1). Provided the sample is initially wired in this way, the switching conventions outlined here will all be representative and valid for the measurement of the sample properties.

For an individual voltage measurement record in the `.raw` file the exact switching configuration of the ASB is recorded under the parameter 'ASB State'. These status codes correspond to the voltage indices of the preceding figures as related in Table C-2

**Table C-2:** ASB Status parameter code descriptions.

| Voltage Index | ASB Status (Res.) | ASB Status (Hall) | Channel | Description | ASB Command |
|---|---|---|---|---|---|
| 1 | 0x1000 | 0x1008 | 1 | Nominal | A |
| 2 | 0x1001 | 0x1009 | 1 | Nominal, current reversed | B |
| 3 | 0x1002 | 0x100A | 1 | 90 deg. rotation | HA |
| 4 | 0x1003 | 0x100B | 1 | 90 deg. rotation, current reversed | HB |
| 5 | 0x1004 | 0x100C | 1 | 180 deg. rotation | NA |
| 6 | 0x1005 | 0x100D | 1 | 180 deg. rotation, current reversed | NB |
| 7 | 0x1006 | 0x100E | 1 | 270 deg. rotation | HNA |
| 8 | 0x1007 | 0x100F | 1 | 270 deg. rotation, current reversed | HNB |
| 1 | 0x2000 | 0x2080 | 2 | Nominal | C |
| 2 | 0x2010 | 0x2090 | 2 | Nominal, current reversed | D |
| 3 | 0x2020 | 0x20A0 | 2 | 90 deg. rotation | JC |
| 4 | 0x2030 | 0x20B0 | 2 | 90 deg. rotation, current reversed | JD |
| 5 | 0x2040 | 0x20C0 | 2 | 180 deg. rotation | PC |
| 6 | 0x2050 | 0x20D0 | 2 | 180 deg. rotation, current reversed | PD |
| 7 | 0x2060 | 0x20E0 | 2 | 270 deg. rotation | JPC |
| 8 | 0x2070 | 0x20F0 | 2 | 270 deg. rotation, current reversed | JPD |
| 1 | 0x4000 | 0x4800 | 3 | Nominal | E |
| 2 | 0x4100 | 0x4900 | 3 | Nominal, current reversed | F |
| 3 | 0x4200 | 0x4A00 | 3 | 90 deg. rotation | LE |
| 4 | 0x4300 | 0x4B00 | 3 | 90 deg. rotation, current reversed | LF |
| 5 | 0x4400 | 0x4C00 | 3 | 180 deg. rotation | RE |
| 6 | 0x4500 | 0x4D00 | 3 | 180 deg. rotation, current reversed | RF |
| 7 | 0x4600 | 0x4E00 | 3 | 270 deg. rotation | LRE |
| 8 | 0x4700 | 0x4F00 | 3 | 270 deg. rotation, current reversed | LRF |

The final column in Table C-2 gives the character code used to trigger this configuration via serial communication with the ASB. These are correct provided the appropriate nominal state (ZS/ZU/ZW for Ch1/2/3 resistivity; ZT/ZV/ZX for Ch1/2/3 Hall) was first established. For more information on direct serial communication with the ASB, please reach out to apps@qdusa.com.