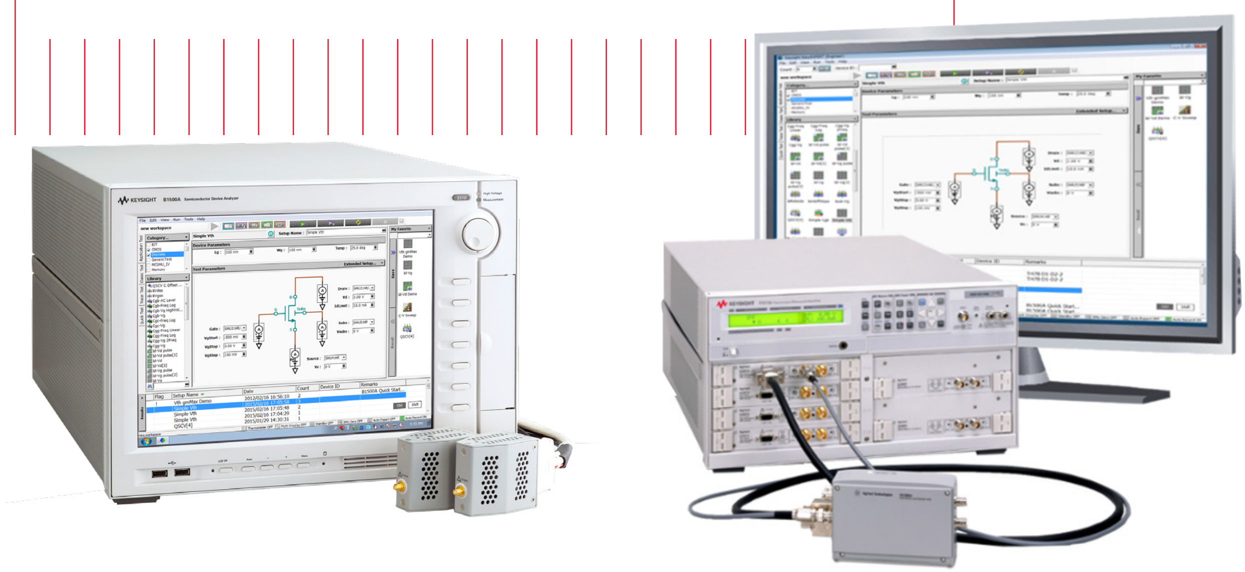
Keysight Technologies

Sheet Resistance/Resistivity Measurement Using a Source/Measurement Unit (SMU)

Precision Current-Voltage Analyzer Series

Application Note



Unlocking Measurement Insights

Introduction

Resistivity is a fundamental characteristic of electrical materials. As well as being the basic measurement for research into new materials such as graphene, carbon nanotube etc, it can also be used to monitor and control the thin layer deposition process for wafer fabrication, where sheet resistance measurement is typically performed to obtain the resistivity.

This application note explains the measurement process and provides advice and practical examples using the Keysight Technologies, Inc. Precision Current-Voltage Analyzer and EasyEXPERT software. Because resistivity measurement requires equipment that can source the current and measure the voltage or vice versa, the Source/Measurement Unit (SMU) of the analyzer enables you to easily and quickly facilitate the measurement, with the use of the powerful analysis capabilities of EasyEXPERT software.

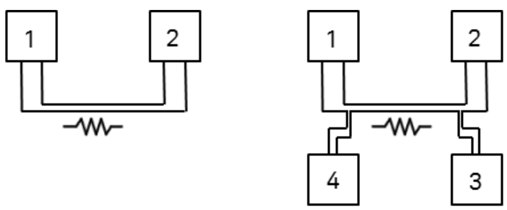
Basics of Resistance Measurement

What is a sheet resistance measurement

When measuring the resistance of sheet form materials, confusion can arise between measuring the resistance in the sheet form and the sheet resistance/resistivity. Some examples of this are show in the following.

Resistor in sheet form

Figure 1 shows two examples of sheet form resistors. The resistor is formed as a narrow line in the center between the contact pads. Figure 1(a) has two contact pads and Figure 1(b) has four pads. In this case, the unit of resistance measurement is ohm (Ω).



(a) Two pads sheet resistor (b) Four pad sheet resistor

Figure 1. Sheet form resistor example.

Sheet resistance/resistivity

Sheet resistance/resistivity is the resistance of a square of conductive thin film with uniform thickness. The measurement unit typically used is Ω/square. The sheet resistance is measured using the Van Der Pauw technique with example test structures as shown in Figure 2.

When the sheet resistance is foursquare shaped as shown in Figure 2, the sheet resistance can be more easily obtained with a simple measurement. Figure 2 (a) and (b) is an example of the metal film fabricated with four contact pads. Figure 2(c) does not have the contact pads, and measurement has to be made by contacting to the four corners of the sheet. Sheet resistance or resistivity Rs can be obtained using the following formula.

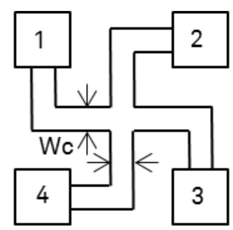
$$Rs = \frac{\rho}{\ln 2} \times \frac{V_{23}}{I_{14}}$$

where,

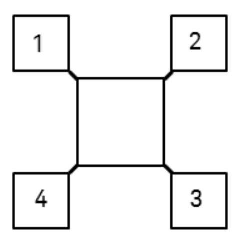
Rs= Sheet resistance measured using a Greek cross bridge or Van der Pauw sheet (ohm/square)

V_{23}= Voltage measured between contacts 2 and 3, or two adjacent pads
I_{14}= Current forced between contacts 1 and 4, or two adjacent pads

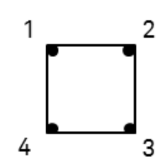
In this application note, the measurement method mainly discussed is the Van Der Pauw method.



(a) Greek cross bridge



(b) Van Der Pauw
(Foursquare with pads)



(c) Van Der Pauw
(Foursquare without pads)

Figure 2. Foursquare shaped sheet resistor example for Van Der Pauw measurement.

Ideal resistance measurement

Figure 3 illustrates a typical example of how a resistance is measured. A voltage is applied to a resistor device, the current is measured and the resistance (R) is calculated using the following equation:

R = Vs/Im

where Vs is a source voltage and Im is the measured current.

This simple measurement approach provides enough accuracy, when the error factors are relatively small compared to the device resistance. For example, residual resistance of a cable and contact resistance is a typical error factor.

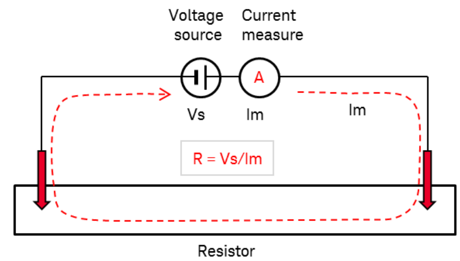


Figure 3. Basic resistance measurement block diagram.

More significant errors in low resistance measurement

When the resistance to be measured becomes low, various errors becomes more significant. It is important to pay attention to the error factors as shown in Figure 4.

- Residual resistance including the cable resistance and the contact resistance
- Offset voltage, thermo-EMF (electromotive force) and the drift of the voltmeter or the voltage source
- Joule heating
- Noise and measurement resolution

These errors degrade the low resistance measurement accuracy, and it is important to eliminate these errors. The following section introduces measurement techniques and know-hows to eliminate the errors and to perform an accurate low resistance measurement.

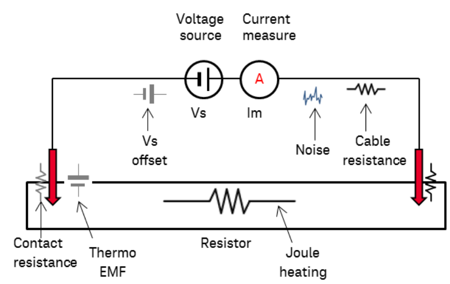


Figure 4. Error sources in the resistance measurement.

Techniques to eliminates errors in low resistance measurement

Kelvin connection to reduce the residual resistance error

Figure 5 shows the Kelvin connection, often called 4-wire connection. It is a well known measurement technique used for low resistance measurement where the residual resistance of connection cable and contact cannot be ignored.

For ideal resistance measurement, the resistance value can be calculated using Vs and Im. However, when the residual resistances of cable Rw and contact Rc are more significant, the calculated value includes them in addition to the resistor R, as follows.

Vs/Im = R+Rw+Rc

To eliminate the Rw and Rc, it is necessary to use the actual voltage applied to the resister R, instead of the applied voltage by the voltage source. As shown in Figure 5, Kelvin connection applies a constant voltage Vs between the two points of the resistor, and measures the flowing current Im. In addition, the voltage Vm is measured between another two points located inside of the current path. Since the input impedance of the voltmeter is very high, the current doesn't flow into the voltmeter, and voltage between the resistance can be measured accurately. As a result, the resistance value is calculated by using Vm and Im without Rw and Rc, as follows.

R = Vm/Im

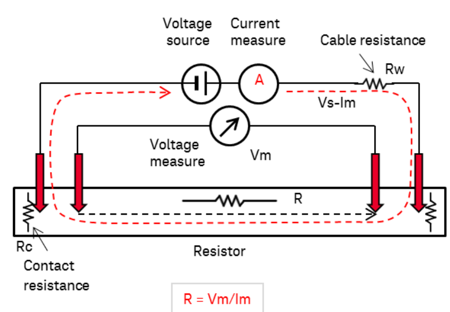


Figure 5. Kelvin connection with voltage source

As shown in Figure 6, there is another method of using a constant current source instead of voltage source. In this case, the resistance value is calculated by using the Is, as follows.

R = Vm/Is

The constant current method is more widely used for typical measurement, because the current sourcing method can eliminate the error caused by the offset voltage of the voltage source.

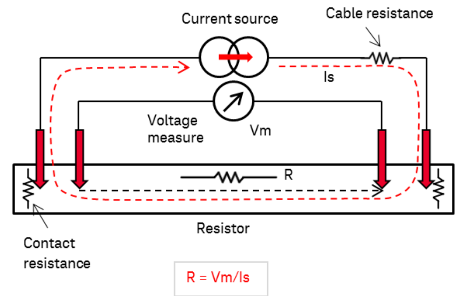


Figure 6. Kelvin connection with current source

Reverse current method to cancel thermo-EMF and offset voltage

When measuring the voltage, it is necessary to consider the following points:

1. Voltmeter offset and thermo-EMF (electromotive force)
2. Drift of the voltmeter offset and thermo-EMF

The thermo-EMF is a voltage generated between the interface of two different metals and can be a voltage offset error. To cancel any voltage offset including thermo-EMF, the reverse current method as shown in Figure 7 should be used. As shown in Figure 7(a), the voltage between the resistance, Vmpos, is at first measured by the forward current +lsp. The voltage between the resistance, Vmneg, is then measured again by the reversed current - lsn, as shown in Figure 7(b). By using the Vmpos, Vmneg and ls, the resistance R can be calculated, eliminating the offset voltage, as follows.

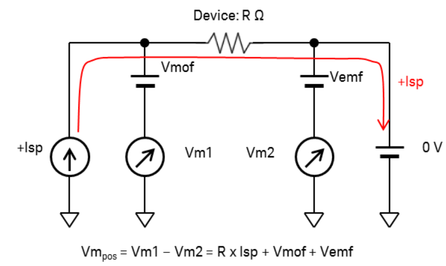
(Vmpos - Vmneg)/2/Is
= ((R x Isp + Vmof + Vemf) - (R x (-Isn) + Vmof + Vemf))/2/Is
= R x (Isp + Isn)/2/Is
= R x (2 x Is) /2/Is
= R
(Is = Isp = Isn)

The Vmof represents the total offset voltage of Vm1 and Vm2, and Vemf represents the total EMF in the voltage measurement path. Because these errors are included in both measurements, taking subtraction of these two measurements can provide the R, eliminating these error factors. Here the thermo-EMF is assumed the same for both Isp and Isn.

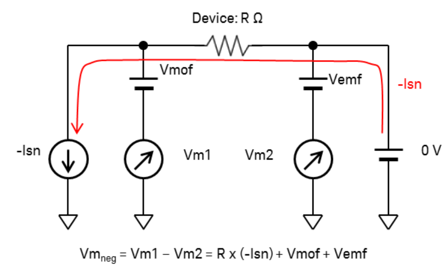
When considering drift factors, it is important to remember that they can vary over time and the measurement must be undertaken while they are stable. The drift is mainly caused by temperate change, so it is important to perform the measurement whilst keeping constant the temperature of the room and the resistance device after warming up the measurement instrument adequately.

The thermo-EMF also depends on the temperature change. Therefore, it is also important to keep the device temperature constant. In practice, it can be difficult to manage the temperature of the device so is necessary to reduce the power and current to minimize the Joule heating. Handling the Joule heating is important when measuring sheet resistance, especially with small geometries that are likely to heat up. This temperature increase, in turn increases the resistance of the sheet material, possibly causing an over-estimate of the sheet resistance.

When the power is limited to prevent the temperature increase, the current is also limited. As a result, the measured voltage between the resistance tends to be small, if the resistance is low. According to the range of measured voltage, it is necessary to choose the appropriate voltmeter to obtain the most accurate measurement.



(a) Positive Is (Forward Is)



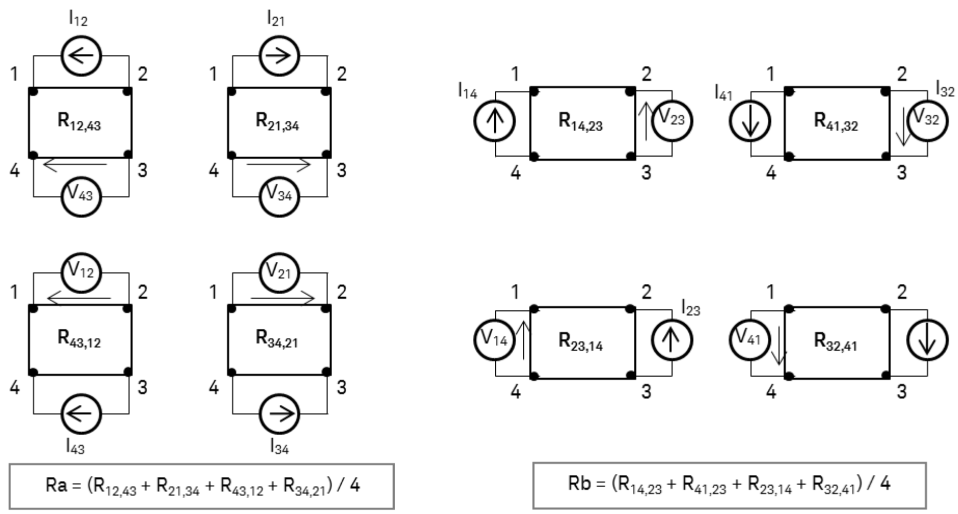
(b) Negative Is (Reverse Is)

Figure 7. Vm and EMF offset can be eliminated by measuring positive Is and negative Is.

Van Der Pauw technique for non-square shaped sheet resistance

This section provides information on how to measure sheet resistance using the Van Der Pauw technique for any rectangular shaped thin resistor sheet. When the sheet shape is non-square or rectangular shape, it requires a series of more complex measurement and calculations.

The Van Der Pauw technique requires the resistance measurement to be performed eight times, as shown in Figure 8. The current polarity and port of measurement must be switched each time, for example, it is necessary to source the current from port 1 to port 2 and measure the voltage between port 4 and port 3 in order to measure the R12, 43, as shown in the left corner of Figure 8. With the results of the eight measurements, the sheet resistance is obtained from the Newton-Raphson method by using average resistance of vertical direction resistance Ra and horizontal direction resistance Rb.



(a) Vertical direction R measurement

(b) Horizontal direction R measurement

Figure 8. Eight resistance measurements using the Van Der Pauw technique for non-square shaped sheet material.

Low resistance measurement using SMU/EasyEXPERT Software

Using a SMU for resistance measurement

As discussed in the previous sections, the resistance measurement requires a coordinated combination of the voltage source, current source, voltmeter, and current meter. In addition, the reverse current method requires a current source that can apply the positive and negative polarity of current without switching. The Source/Measure Unit (SMU) is a solution for these requirements.

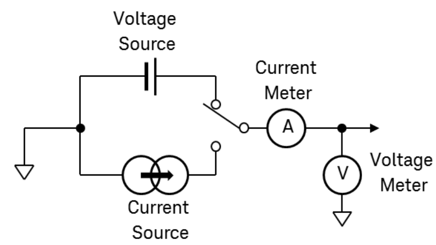


Figure 9. Simplified SMU schematic.

Figure 9 shows a simplified equivalent circuit of the SMU. The SMU integrates multiple source and measurement capabilities into one compact form factor. It can operate as a seamless 4- quadrant precision voltage/current source and an accurate voltage/current meter so that it can source the voltage or current and simultaneously measure current or voltage. It allows you to quickly and easily perform accurate resistance measurement.

The Keysight Precision Current-Voltage Analyzer series provides a variety of SMU solutions for all budgets, with voltage/current range up to 200V/1A and resolution down to 0.1fA, allowing you to choose the appropriate solution to meet your measurement needs.

An example setup of a reverse current method

Figure 10 shows an example setup of a reverse current method using two SMUs. The high side of resistance is connected to the SMU1. It is used for current source and measures the voltage using the remote sensing. The low side is connected to SMU2. SMU2 is set to 0V and the remote sense must be connected close to the device. Remote sense works to keep the SMU's voltage as specified at the sensing point. As a result, the Vm2 is regarded as 0V, though SMU2 doesn't actually measure the Vm2. Reverse current condition can be measured vice versa by changing the setting of SMU1 and 2 without changing the connections.

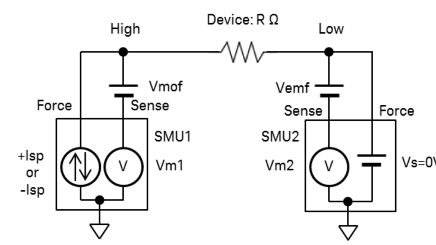


Figure 10. Example setup of reverse current method using two SMUs

Typically in the low resistance measurement, the measured voltage between the resistor is small. It is important to choose the measurement range to get the appropriate resolution and level of accuracy. The SMU's auto-range is helpful to perform the measurement in the best range.

When measuring the low resistance it is important to minimize noise. The SMU provides an averaging feature that allows you to specify the number of PLC (Power line Cycle) to reduce the noise on the power line.

The reverse current method requires a calculation to obtain the resistance. The EasyEXPERT software provides a powerful built-in function that allows you to calculate the resistance value automatically after the measurement.

An example of the measurement set up for the Van Der Pauw technique

This measurement can also easily be made using four SMUs as shown in Figure 11. Since the SMU can freely switch between the force current/voltage and measure current/voltage mode, the other seven resistances in the configuration of Figure 8 are similarly measured without changing the connection.

This measurement method uses the reverse polarity technique minimizing the effect of offsetting the voltage of the SMU and the thermo-EMF.

The average resistance is set as Ra in the vertical direction and Rb in the horizontal direction, as shown in Figure 8. The final sheet resistance is calculated by using Newton-Raphson method by assuming the sheet resistance is uniform.

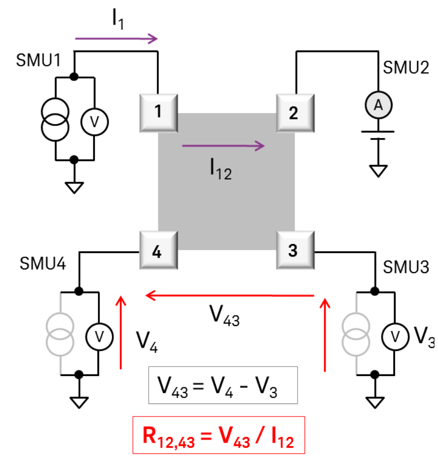


Figure 11. Van Der Pauw resistance measurement definition for R12,43 measurement by the B1500A.

EasyEXPERT Application Test for Van Der Pauw measurement

The Van Der Pauw measurement application is available in the application library of the latest EasyEXPERT group+ software (the revision that follows 6.1). Figure 12 shows the GUI of this application test. And Figure 13 shows the measurement example including each of eight R components measurement values, average of vertical and horizontal direction resistors, and the sheet resistance Rs obtained from the Newton-Raphson method. You can easily execute the complex Van Der Pauw measurement using the SMU's measurement capability and EasyEXPERT's powerful measurement sequencing and built-in calculation capabilities.

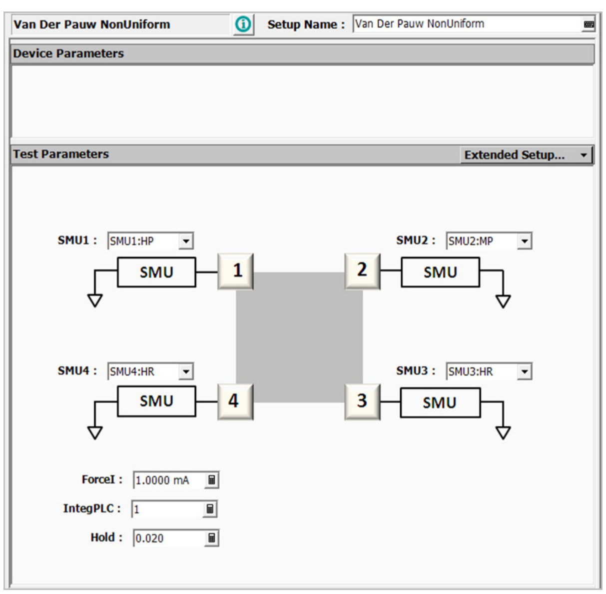


Figure 12. Van Der Pauw application test of EasyEXPERT software.

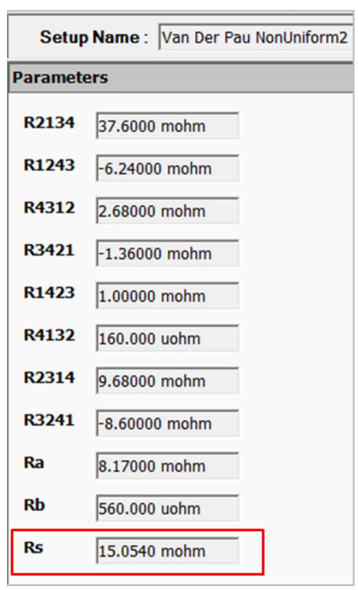


Figure 13. Van Der Pauw application test measurement example

Summary

In this application note, sheet resistance measurement techniques are introduced. To perform the resistance measurements requires the use of a voltage/current source and coordinating voltage/current meter. The Keysight Precision Current-Voltage Analyzer series allows you to quickly and easily perform accurate resistance measurements using the Source/Measure Unit (SMU) measurement functions and the powerful capabilities of EasyEXPERT, alongside the ready to use Van Der Pauw application test.

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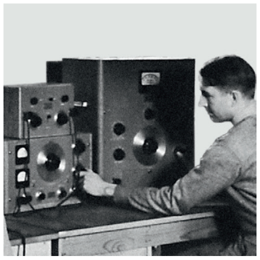
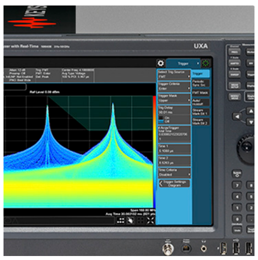


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