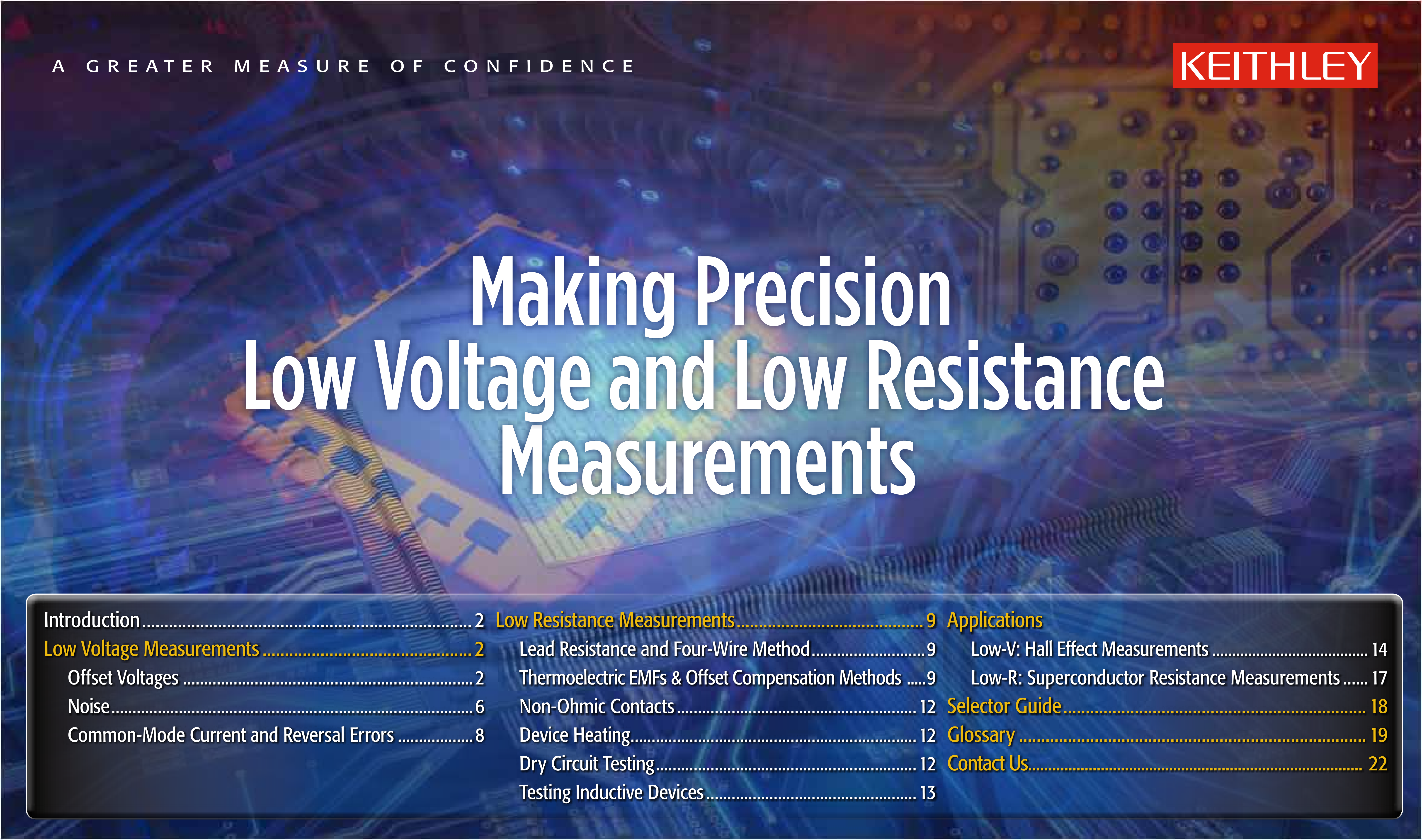

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KEITHLEY

Making Precision Low Voltage and Low Resistance Measurements

Applications

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Low Voltage Measurements

Introduction

Low voltage and low resistance measurements are often made on devices and materials with low source impedance. This e-handbook discusses several potential sources of error in low voltage measurements and how to minimize their impact on measurement accuracy, as well as potential error sources for low resistance measurements, including lead resistance, thermoelectric EMFs, non-ohmic contacts, device heating, dry circuit testing, and measuring inductive devices.

Significant errors may be introduced into low voltage measurements by offset voltages and noise sources that can normally be ignored when measuring higher voltage levels. These factors can have a significant effect on low voltage measurement accuracy.

Offset Voltages

Ideally, when a voltmeter is connected to a relatively low impedance circuit in which no voltages are present, it should read zero. However, a number of error sources in the circuit may be seen as a non-zero voltage offset. These sources include thermoelectric EMFs, offsets generated by rectification of RFI (radio frequency interference), and offsets in the voltmeter input circuit.

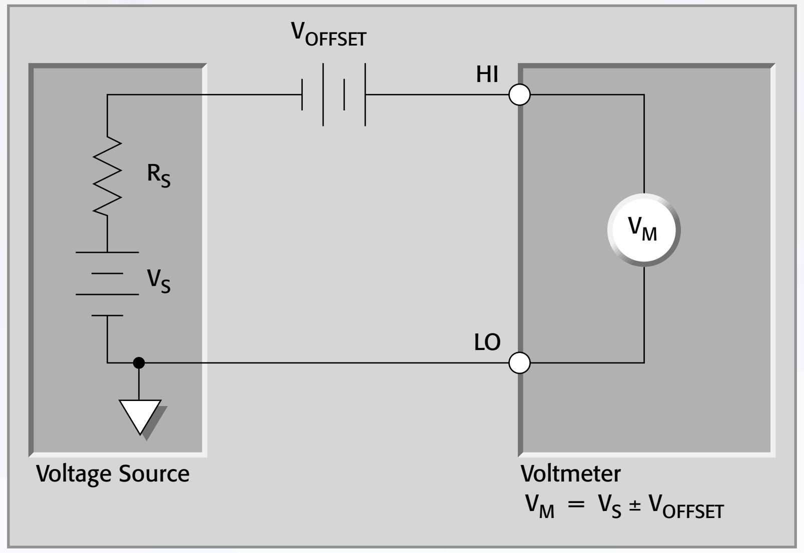


Figure 1: Effects of Offset Voltages on Voltage Measurement Accuracy

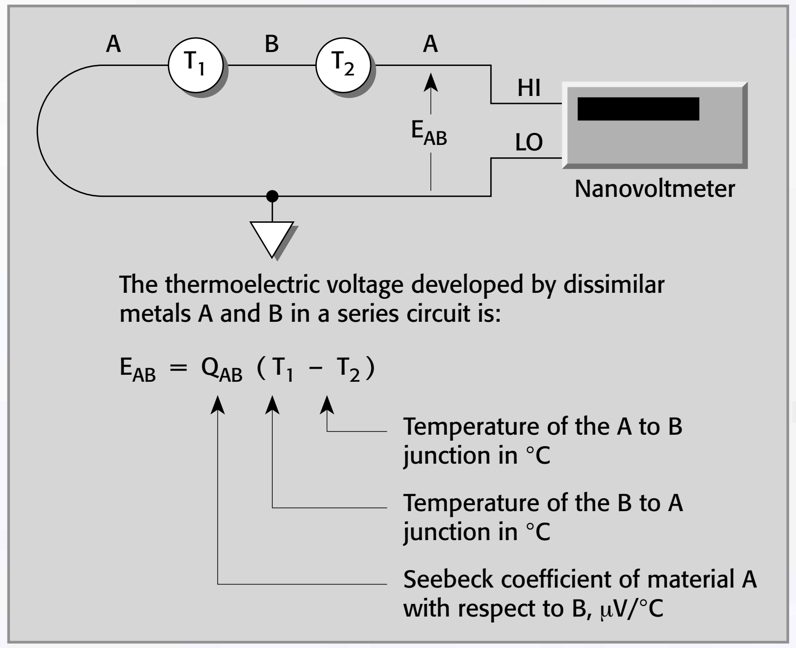
As shown in **Figure 1**, any offset voltage (V_{OFFSET}) will add to or subtract from the source voltage (V_S) so that the voltage measured by the meter becomes:

$$V_M = V_S \pm V_{OFFSET}$$

The relative polarities of the two voltages will determine whether the offset voltage adds to or subtracts from the source voltage. Steady offsets can generally be nulled out by shorting the ends of the test leads together, then enabling the instrument's zero (relative) feature. Note, however, that cancellation of offset drift may require frequent rezeroing, particularly in the case of thermoelectric EMFs.

THERMOELECTRIC EMFs

Thermoelectric voltages (thermoelectric EMFs) are the most common source of errors in low voltage measurements. These voltages are generated when different parts of a circuit are at different temperatures and when conductors made of dissimilar materials are joined together, as shown in **Figure 2**. The Seebeck coefficients (Q_{AB}) of various materials with respect to copper are summarized in **Table 1**.



The thermoelectric voltage developed by dissimilar metals A and B in a series circuit is:

$$E_{AB} = Q_{AB} (T_1 - T_2)$$

Temperature of the A to B junction in °C

Temperature of the B to A junction in °C

Seebeck coefficient of material A with respect to B, µV/°C

Figure 2: Thermoelectric EMFs

FEATURED RESOURCES

- Troubleshooting Low Voltage Measurement Problems

- Accurate Low-Resistance Measurements Start with Identifying Sources of Error

ADDITIONAL RESOURCES

- Understanding Low Voltage Measurements
- Problem: Errors in Low Resistance Measurements

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Low Voltage Measurements

Table 1: Seebeck Coefficients

Paired Materials*	Seebeck Coefficient, Q_{AB}
Cu - Cu	≤0.2 µV/°C
Cu - Ag	0.3 µV/°C
Cu - Au	0.3 µV/°C
Cu - Pb/Sn	1–3 µV/°C
Cu - Si	400 µV/°C
Cu - Kovar	~40–75 µV/°C
Cu - CuO	~1000 µV/°C

* Ag = silver Au = gold Cu = copper CuO = copper oxide
Pb = lead Si = silicon Sn = tin

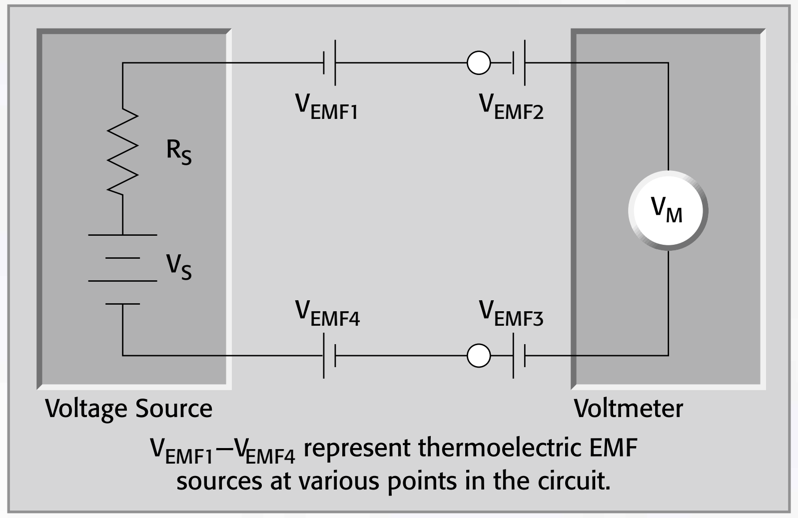
Constructing circuits using the same material for all conductors minimizes thermoelectric EMF generation. For example, crimping copper sleeves or lugs onto copper wires results in copper-to-copper junctions, which generate minimal thermoelectric EMFs. Also, connections must be kept clean and free of oxides. Crimped copper-to-copper connections, called "cold welded," do not allow oxygen penetration and may have a Seebeck coefficient of ≤0.2µV/°C, while Cu-CuO connections may have a coefficient as high as 1mV/°C.

Minimizing temperature gradients within the circuit also reduces thermoelectric EMFs. A technique for minimizing such gradients is to place corresponding pairs of junctions in close proximity to one another and to provide good thermal coupling to a common, massive heat sink. Electrical insulators having high thermal conductivity must be used, but, since most electrical insulators don't conduct heat well, special insulators such as hard anodized aluminum, beryllium oxide, specially filled epoxy resins, sapphire, or diamond must be used to couple junctions to the heat sink.

Allowing test equipment to warm up and reach thermal equilibrium in a constant ambient temperature also minimizes thermoelectric EMF effects. The instrument zero feature can compensate for any remaining thermoelectric EMF, provided it is relatively constant. To keep ambient temperatures constant, equipment should be kept away from direct sunlight, exhaust fans, and similar sources of heat flow or moving air. Wrapping connections in insulating foam (e.g., polyurethane) also minimizes ambient temperature fluctuations caused by air movement.

CONNECTIONS TO AVOID THERMOELECTRIC EMFs

Connections in a simple low voltage circuit, as shown in **Figure 3**, will usually include dissimilar materials at different temperatures. This produces a number of thermoelectric EMF sources, all connected in series with the voltage source and the meter. The meter reading will be the algebraic sum of all these sources. Therefore, it is important that the connection between the signal source and the measuring instrument doesn't interfere with the reading.



V_{EMF1}–V_{EMF4} represent thermoelectric EMF sources at various points in the circuit.

Figure 3: Connections from Voltage Source to Voltmeter

If all the connections can be made of one metal, the amount of thermoelectric EMF added to the measurement will be negligible. However, this may not always be possible. Test fixtures often use spring contacts, which may be made of phosphor-bronze, beryllium-copper, or other materials with high Seebeck coefficients. In these cases, a small temperature difference may generate a large enough thermoelectric voltage to affect the accuracy of the measurement.

If dissimilar metals cannot be avoided, an effort should be made to reduce the temperature gradients throughout the test circuit by use of a heat sink or by shielding the circuit from the source of heat.

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Low Voltage Measurements

Measurements of sources at cryogenic temperatures pose special problems since the connections between the sample in the cryostat and the voltmeter are often made of metals with lower thermal conductivity than copper, such as iron, which introduces dissimilar metals into the circuit. In addition, since the source may be near zero Kelvin while the meter is at 300K, there is a very large temperature gradient. Matching the composition of the wires between the cryostat and the voltmeter and keeping all dissimilar metal junction pairs at the same temperature allows making very low voltage measurements with good accuracy.

REVERSING SOURCES TO CANCEL THERMOELECTRIC EMFS

When measuring a small voltage, such as the difference between two standard cells or the difference between two thermocouples connected back-to-back, the error caused by stray thermoelectric EMFs can be canceled by taking one measurement, then carefully reversing the two sources and taking a second measurement. The average of the difference between these two readings is the desired voltage difference.

In **Figure 4**, the voltage sources, V_a and V_b, represent two standard cells (or two thermocouples). The voltage measured in **Figure 4a** is:

$$V_1 = V_{emf} + V_a - V_b$$

The two cells are reversed in **Figure 4b** and the measured voltage is:

$$V_2 = V_{emf} + V_b - V_a$$

The average of the difference between these two measurements is:

$$\frac{V_1 - V_2}{2} = \frac{V_{emf} + V_a - V_b - V_{emf} - V_b + V_a}{2} \text{ or } V_a - V_b$$

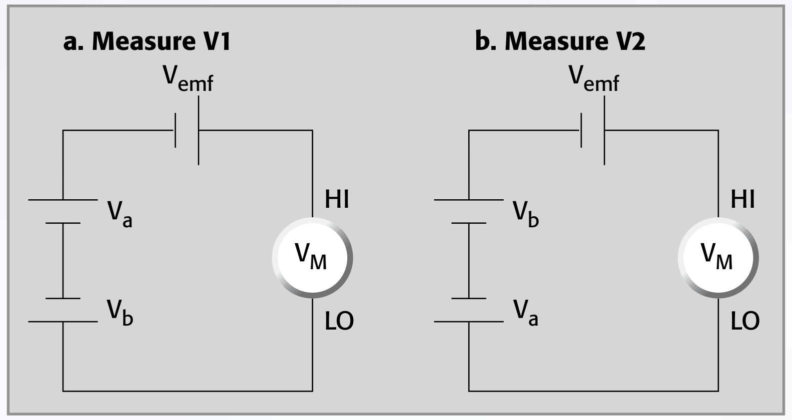

Figure 4: Reversing Sources to Cancel Thermoelectric EMFs

Notice that this measurement technique effectively cancels out the thermoelectric EMF term (V_{emf}), which represents the algebraic sum of all thermoelectric EMFs in the circuit except those in the connections between V_a and V_b. If the measured voltage is the result of a current flowing through an unknown resistance, then either the current-reversal method or the offset-compensated ohms method may be used to cancel the thermoelectric EMFs.

RFI/EMI

RFI (Radio Frequency Interference) and EMI (Electromagnetic Interference) are general terms used to describe electromagnetic interference over a wide range of frequencies across the spectrum. RFI or EMI can be caused by sources such as TV or radio broadcast signals or it can be caused by impulse sources, as in the case of high voltage arcing. In either case, the effects on the measurement can be considerable if enough of the unwanted signal is present.

RFI/EMI interference may manifest itself as a steady reading offset or it may result in noisy or erratic readings. A reading offset may be caused by input amplifier overload or DC rectification at the input.

RFI and EMI can be minimized by taking several precautions when making sensitive measurements. The most obvious precaution is to keep all instruments, cables, and DUTs as far from the interference source as possible. Shielding the test leads and the DUT (**Figure 5**) will often reduce interference effects to an acceptable level. Noise shields should be connected to input LO. In extreme cases, a specially constructed screen room may be necessary to attenuate the troublesome signal sufficiently.

If all else fails to prevent RF interference from being introduced into the input, external filtering of the device input paths may be required, as shown in **Figure 6**. In many cases, a simple one-pole filter may be sufficient; in more difficult cases, multiple-pole notch or band-stop filters may be required. In particular, multiple capacitors of different values may be connected in parallel to provide low impedance over a wide frequency range. Keep in mind, however, that such filtering may have other detrimental effects, such as increased response time on the measurement.

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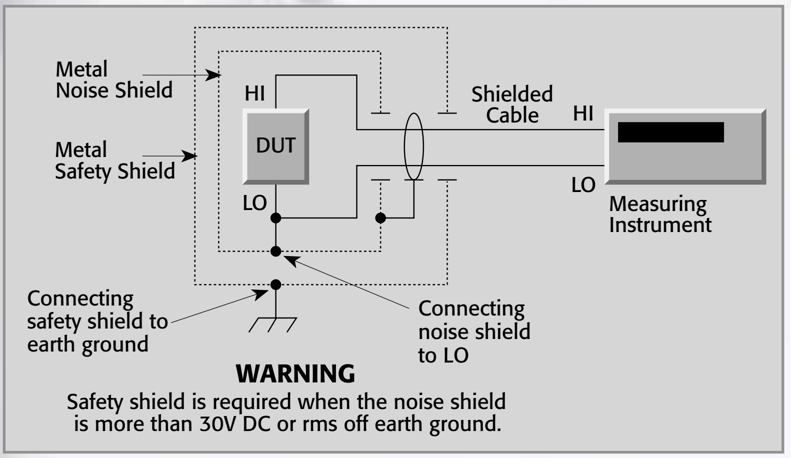

Figure 5: Shielding to Attenuate RFI/EMI Interference

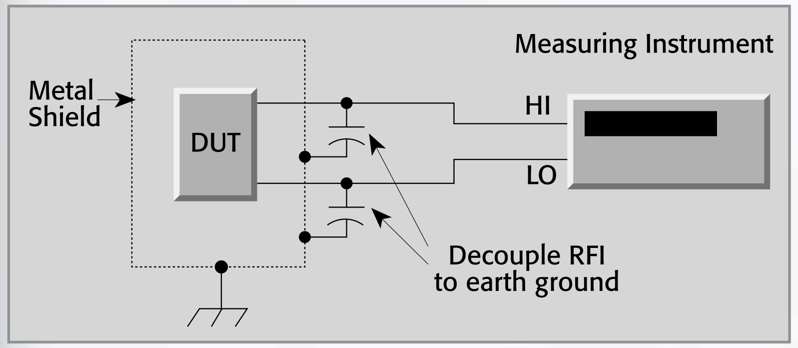

Figure 6: Shielded Connections to Reduce Inducted RFI/EMI

INTERNAL OFFSETS

Nanovoltmeters will rarely indicate zero when no voltage is applied to the input, since there are unavoidable voltage offsets present in the input of the instrument. A short circuit can be connected across the input terminals and the output can then be set to zero, either by front panel zero controls or by computer control. If the short circuit has a very low thermoelectric EMF, this can be used to verify input noise and zero drift with time. Clean, pure copper wire will usually be suitable. However, the zero established in this manner is useful only for verification purposes and is of no value in the end application of the instrument.

If the instrument is being used to measure a small voltage drop resulting from the flow of current through a resistor, the following procedure will result in a proper zero. First, the instrument should be allowed to warm up for the specified time, usually one to two hours. During this time, the connections should be made between the device under test and the instrument. No current should be supplied to the device under test to allow the temperature gradients to settle to a minimum, stable level. Next, the zero adjustment should be made. In some instruments, this is done by pressing REL (for Relative) or ZERO button. The instrument will now read zero. When the test current is applied, the instrument will indicate the resulting voltage drop. In some applications, the voltage to be measured is always present and the preceding procedure cannot be used. For example, the voltage difference between two standard cells is best observed by reversing the instrument connections to the cells and averaging the two readings. This same technique is used to cancel offsets when measuring the output of differential thermocouples. This is the same method used to cancel thermoelectric EMFs.

ZERO DRIFT

Zero drift is a change in the meter reading with no input signal (measured with the input shorted) over a period of time. The zero drift of an instrument is almost entirely determined by the input stage. Most nanovoltmeters use some form of chopping or modulation of the input signal to minimize the drift.

The zero reading may also vary as the ambient temperature changes. This effect is usually referred to as the temperature coefficient of the voltage offset. In addition, an instrument may display a transient temperature effect. After a step change in the ambient temperature, the voltage offset may change by a relatively large amount, possibly exceeding the published specifications.

The offset will then gradually decrease and eventually settle to a value close to the original value. This is the result of dissimilar metal junctions in the instrument with different thermal time constants. While one junction will adjust to the new ambient temperature quickly, another changes slowly, resulting in a temporary change in voltage offset.

To minimize voltage offsets due to ambient temperature changes in junctions, make measurements in a temperature controlled environment and/or slow down temperature changes by thermally shielding the circuit.

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Low Voltage Measurements

Noise

Significant errors can be generated by noise sources, which include Johnson noise, magnetic fields, and ground loops. An understanding of these noise sources and the methods available to minimize them is crucial to making meaningful low voltage measurements.

JOHNSON NOISE

The ultimate limit of resolution in an electrical measurement is defined by Johnson or thermal noise. This noise is the voltage associated with the motion of electrons due to their thermal energy at temperatures above absolute zero. All voltage sources have internal resistance, so all voltage sources develop Johnson noise. The noise voltage developed by a metallic resistance can be calculated from the following equation:

$$V = \sqrt{4kTBR}$$

where: V = rms noise voltage developed in source resistance

k = Boltzmann's constant, 1.38×10^{-23} joule/K

T = absolute temperature of the source in Kelvin

B = noise bandwidth in hertz

R = resistance of the source in ohms

For example, at room temperature (290K), a source resistance of 10kΩ with a measurement bandwidth of 5kHz will have almost 1μV rms of noise.

Johnson noise may be reduced by lowering the temperature of the source resistance and by decreasing the bandwidth of the measurement. Cooling the sample from room temperature (290K) to liquid nitrogen temperature (77K) decreases the voltage noise by approximately a factor of two.

If the voltmeter has adjustable filtering and integration, the bandwidth can be reduced by increasing the amount of filtering and/or by integrating over multiple power line cycles. Decreasing the bandwidth of the measurement is equivalent to increasing the response time of the instrument, and as a result, the measurement time is much longer. However, if the measurement response time is long, the thermoelectric EMFs associated with the temperature gradients in the circuit become more important. Sensitive measurements may not be achieved if the thermal time constants of the measurement circuit are of the same order as the response time. If this occurs, distinguishing between a change in signal voltage and a change in thermoelectric EMFs becomes impossible.

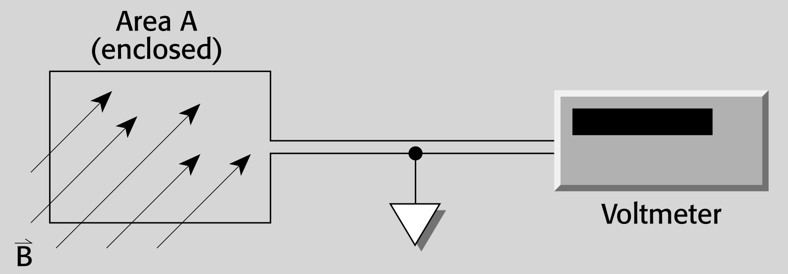
MAGNETIC FIELDS

Magnetic fields generate error voltages in two circumstances: 1) if the field is changing with time, and 2) if there is relative motion between the circuit and the field. Voltages in conductors can be generated from the motion of a conductor in a magnetic field, from local AC currents caused by components in the test system, or from the deliberate ramping of the magnetic field, such as for magnetoresistance measurements. Even the earth's relatively weak magnetic field can generate nanovolts in dangling leads, so leads must be kept short and rigidly tied down.

Basic physics shows that the amount of voltage a magnetic field induces in a circuit is proportional to the area the circuit leads enclose and the rate of change in magnetic flux density, as shown in **Figure 7**. The induced voltage is proportional both to the magnitude of A and $\vec{B}$, as well as to the rate of change in A and $\vec{B}$, so there are two ways to minimize the induced voltage:

- Keep both A and $\vec{B}$ to a minimum by reducing loop area and avoiding magnetic fields, if possible; and
- Keep both A and $\vec{B}$ constant by minimizing vibration and movement, and by keeping circuits away from AC and RF fields.

To minimize induced magnetic voltages, leads must be run close together and magnetically shielded and they should be tied down to minimize movement. Mu-metal, a special alloy with high permeability at low magnetic flux densities and at low frequencies, is a commonly used magnetic shielding material.



The voltage developed due to a field passing through a circuit enclosing a prescribed area is:

$$V_B = \frac{d\phi}{dt} = \frac{d(\vec{B}A)}{dt} = \vec{B}\frac{dA}{dt} + A\frac{d\vec{B}}{dt}$$

Figure 7: Low Voltages Generated by Magnetic Fields

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Low Voltage Measurements

Figure 8 shows two ways of locating the leads from the source to the voltmeter. In **Figure 8a**, a large area is enclosed; thus, a large voltage is developed. In **Figure 8b**, a much smaller area is enclosed because the leads are twisted together, and the voltage induced is considerably reduced. Twisted pair also cancels magnetically induced voltages because each adjacent twist couples a small but alternating polarity (equal) voltage. Conductors that carry large currents should also be shielded or run as twisted pairs to avoid generating magnetic fields that can affect nearby circuits. In addition to these techniques, AC signals from magnetic fields can be filtered at the input of the instrument. If possible, the signal source and the instrument should be physically relocated further away from the interfering magnetic field.

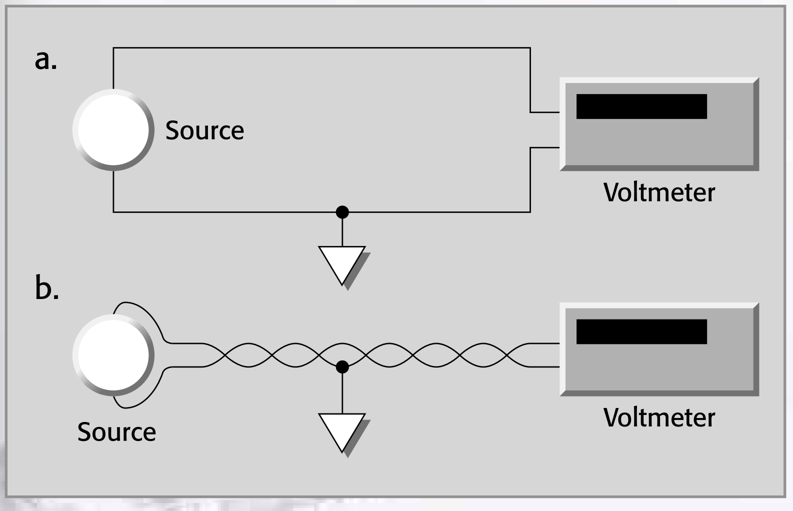


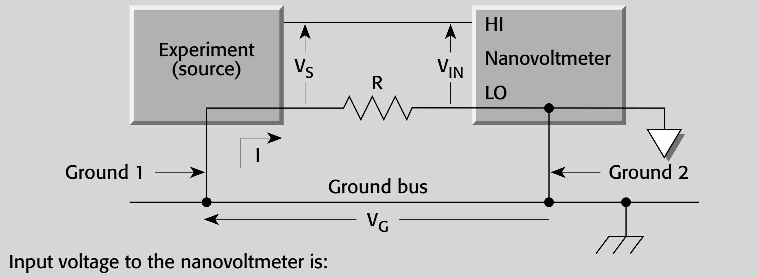
Figure 8: Minimizing Interference from Magnetic Fields

GROUND LOOPS

Noise and error voltages also arise from ground loops. When there are two connections to earth, such as when the source and measuring instruments are both connected to a common ground bus, a loop is formed as shown in **Figure 9a**. A voltage (V_G) between the source and instrument grounds will cause a current (I) to flow around the loop. This current will create an unwanted voltage in series with the source voltage. From Ohm's Law:

$$V_G = IR$$

where V_G = ground loop interfering voltage, R = the resistance in the signal path through which the ground loop current flows, and I = the ground loop current. A typical example of a ground loop can be seen when a number of instruments are plugged into power strips on different instrument racks. Frequently, there is a small difference in potential between the ground points. This potential difference can cause large currents to circulate and create unexpected voltage drops.



Input voltage to the nanovoltmeter is:

$V_{IN} = V_S + V_G$

where V_G = IR, and

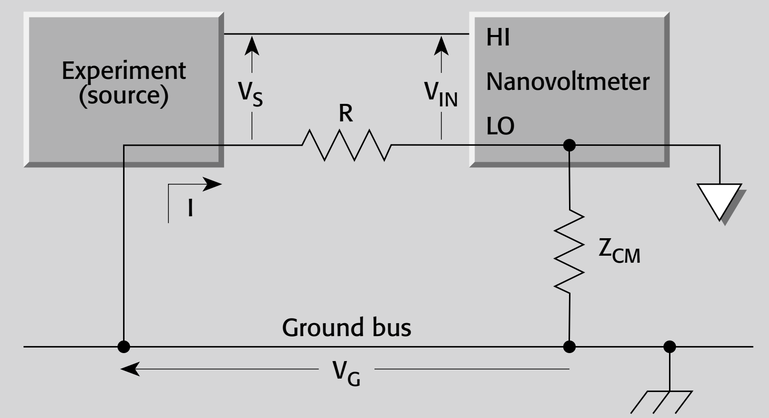
R = Resistance of input LO connection (typically around 00mΩ)

I = Current passing through input LO connection due to ground voltages (V_G) in the ground bus (magnitude may be amperes)

V_S = Source voltage (desired signal)

V_G may exceed V_S by orders of magnitude.

Figure 9a: Multiple Grounds (Ground Loops)



$V_{IN} \approx V_S$, since V_G is now insignificant compared to V_S.

Z_{CM} = Common mode impedance of nanovoltmeter

Figure 9b: Reduced Ground Loops

The cure for such ground loops is to ground all equipment at a single point. The easiest way of accomplishing this is to use isolated power sources and instruments, then find a single, good earth-ground point for the entire system. Avoid connecting sensitive instruments to the same ground system used by other instruments, machinery, or other high power equipment. As shown in **Figure 9b**, ground loops can also be reduced by using a voltmeter with high common mode impedance (Z_{CM}), also known as common mode isolation.

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Low Voltage Measurements

Common-Mode Current and Reversal Errors

Excessive common-mode current can significantly affect low-level voltage measurements. Although common-mode currents are most often associated with noise problems, they can result in large DC offsets in some cases. In the following paragraphs, we will briefly discuss the basic principles behind errors generated by common-mode currents and ways to avoid lead reversal errors.

COMMON-MODE CURRENT

Common-mode current is the current that flows between the instrument's LO terminal and chassis or earth ground. As shown in **Figure 10**, common-mode current (I_{CM}) is caused by capacitive coupling ($C_{COUPLING}$) from the power line through the power transformer. The amplitude of the common-mode current is defined as:

$$I_{CM} = 2\pi f C_{COUPLING} (V_2 \pm V_1)$$

where f is the power line frequency.

Note that the common-mode current flows through the impedance (Z_{CM}), which is present between input LO and chassis ground. As a result, the amplitude of voltage (V_{CM}) depends on the magnitude of Z_{CM} as well as the value of I_{CM}.

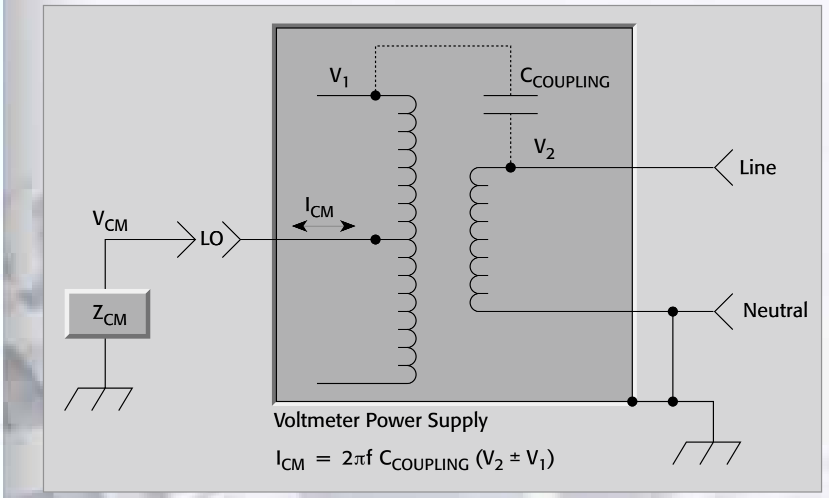


Figure 10: Common Mode Current Generation by Power Line Coupling

COMMON-MODE REVERSAL ERRORS

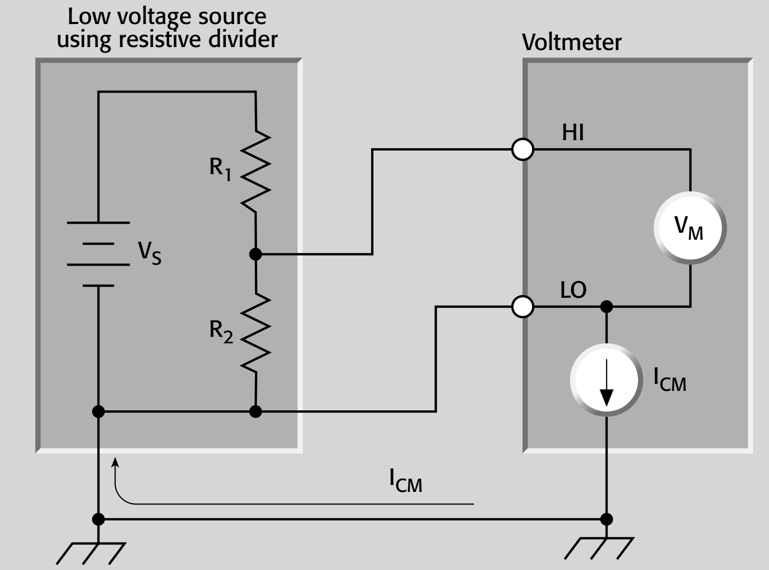
Reversing leads can result in errors caused by common-mode currents. As shown in **Figure 11**, many low voltage sources have internal resistive dividers, which attenuate an internal voltage source to the desired level. For example, the output voltage from the source is defined as:

$$V_{OUTPUT} = V_S \left(\frac{R_2}{R_1 + R_2} \right)$$

With the correct connection scheme shown in **Figure 11a**, the low or chassis side of the voltage source is connected to input LO of the measuring instrument. Any common-mode current (I_{CM}) that may be present flows from the voltmeter input LO to instrument chassis common, through earth ground to voltage source ground. Note that no common-mode current flows through either of the two divider resistors of the voltage source when this connection scheme is used.

If the input leads of the voltmeter are reversed, we have the situation shown in **Figure 11b**. Now, the common-mode current (I_{CM}) flows through R_2, developing a voltage drop, which is added to the voltage to be measured. This added voltage is mainly power line frequency and its effect on the voltmeter reading will depend upon the normal-mode rejection capability of the meter. The reading may become noisy or it may have a constant offset. In some cases, the sensitivity of the meter may be reduced, because the input stages are overloaded. To minimize common-mode reversal errors, choose an instrument with the lowest possible common-mode current. If possible, the voltage source being measured should be isolated from ground.

a. With proper connections, I_{CM} generates no noise or offset.



b. With reversed connections, I_{CM} generates noise and possible offset.

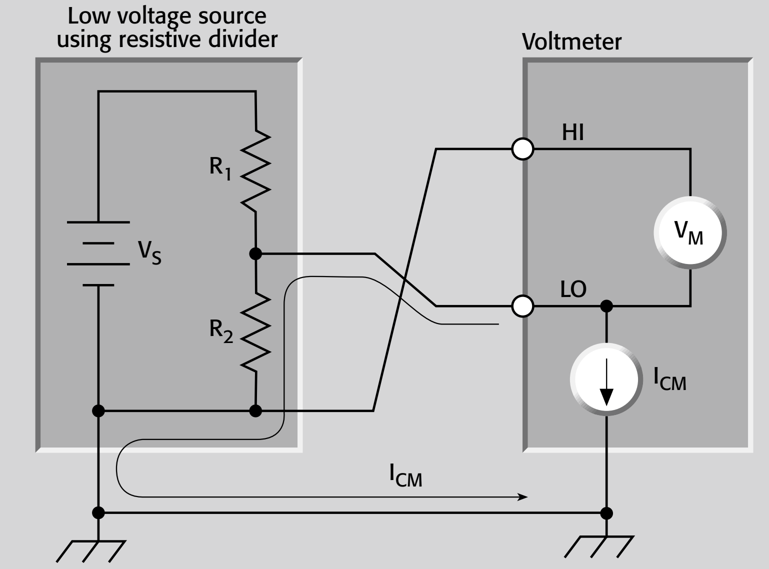


Figure 11: Effects of Reversing Leads on Common Mode Errors

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- AC versus DC Measurement Methods for Low-power Nanotech and Other Sensitive Devices

AC versus DC Measurement Methods for Low-power Nanotech and Other Sensitive Devices

Electrical Measurements On Nanoscale Materials

- Electrical Measurements on Nanoscale Materials

ADDITIONAL RESOURCES

- Low-V Measurement Techniques
- New Instruments Can Lock Out Lock-ins

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Low Resistance Measurements

Lead Resistance and Four-Wire Method

Resistance measurements are often made using the two-wire method shown in **Figure 12**. The test current is forced through the test leads and the resistance (R) being measured. The meter then measures the voltage across the resistance through the same set of test leads and computes the resistance value accordingly. The main problem with the two-wire method as applied to low resistance measurements is that the total lead resistance (R_{LEAD}) is added to the measurement. Because the test current (I) causes a small but significant voltage drop across the lead resistances, the voltage (V_M) measured by the meter won't be exactly the same as the voltage (V_R) directly across the test resistance (R), and considerable error can result. Typical lead resistances lie in the range of 1mΩ to 10mΩ, so it's very difficult to obtain accurate two-wire resistance measurements when the resistance under test is lower than 10Ω to 100Ω (depending on lead resistance).

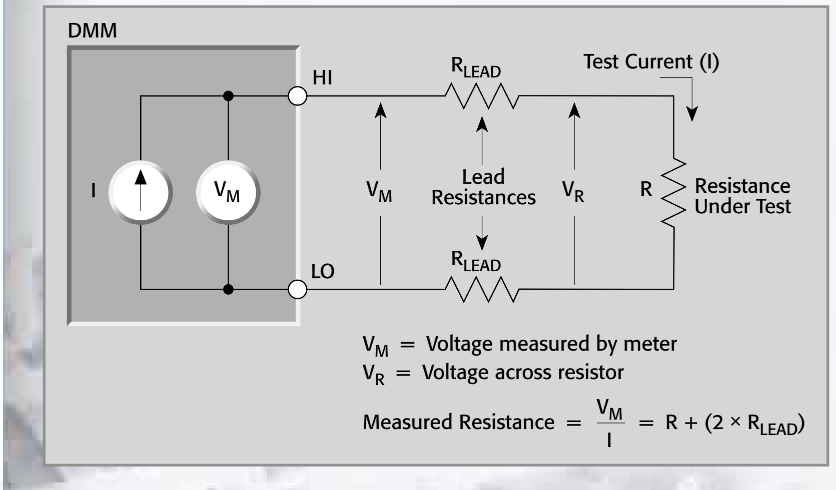


Figure 12: Two-Wire Resistance Measurement

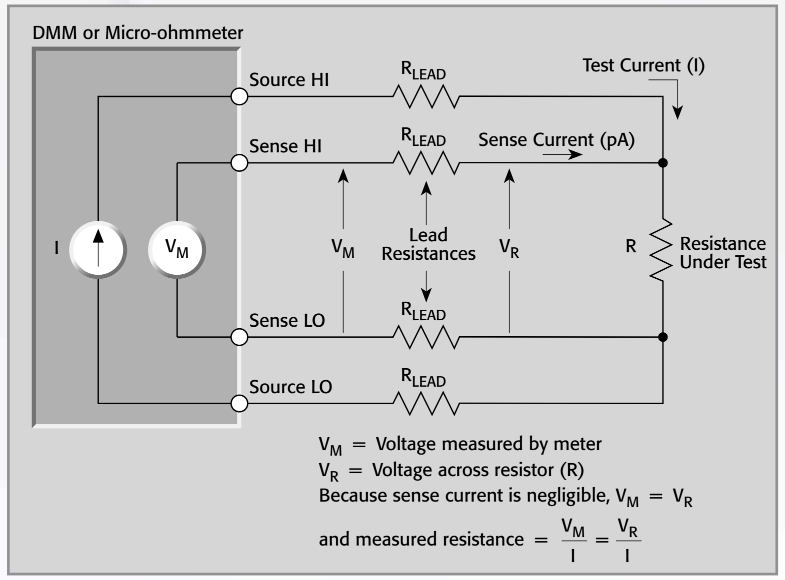


Figure 13: Four-Wire Resistance Measurement

Due to the limitations of the two-wire method, the four-wire (Kelvin) connection method shown in **Figure 13** is generally preferred for low resistance measurements. These measurements can be made using a DMM, micro-ohmmeter, or a separate current source and voltmeter. With this configuration, the test current (I) is forced through the test resistance (R) through one set of test leads, while the voltage (V_M) across the DUT is measured through a second set of leads called sense leads. Although some small current may flow through the sense leads, it is usually negligible and can generally be ignored for all practical purposes. The voltage drop across the sense leads is negligible, so the voltage measured by the meter (V_M) is essentially the same as the voltage (V_R) across the resistance (R). Consequently, the resistance value can be determined much more accurately than with the two-wire method. Note that the voltage-sensing leads should be connected as close to the resistor under test as possible to avoid including the resistance of the test leads in the measurement.

Thermoelectric EMFs and Offset Compensation Methods

Thermoelectric voltages can seriously affect low resistance measurement accuracy. The current-reversal method, the delta method, and the offset-compensated ohms method are three common ways to overcome these unwanted offsets.

CURRENT-REVERSAL METHOD

Thermoelectric EMFs can be canceled by making two measurements with currents of opposite polarity, as shown in **Figure 14**. In this diagram, a voltmeter with a separate bipolar current source is used. With the positive current applied as in **Figure 14a**, the measured voltage is:

$$V_{M+} = V_{EMF} + IR$$

Reversing the current polarity as shown in **Figure 14b** yields the following voltage measurement:

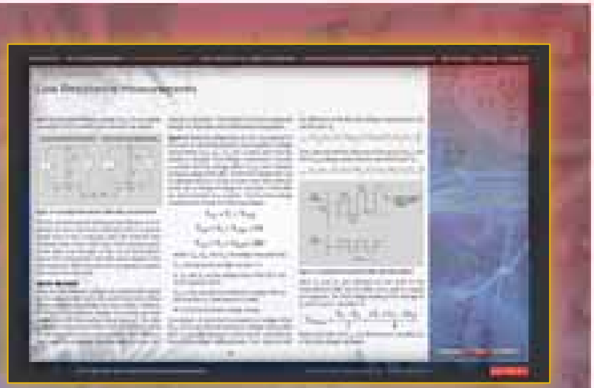
$$V_{M-} = V_{EMF} - IR$$

The two measurements can be combined to cancel thermoelectric EMFs:

$$V_M = \frac{V_{M+} - V_{M-}}{2} = \frac{(V_{EMF} + IR) - (V_{EMF} - IR)}{2} = IR$$

The measured resistance is computed in the usual manner:

$$R = \frac{V_M}{1}$$



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Low Resistance Measurements

Note that the thermoelectric voltage (V_{EMF}) is completely canceled out by this method of resistance calculation.

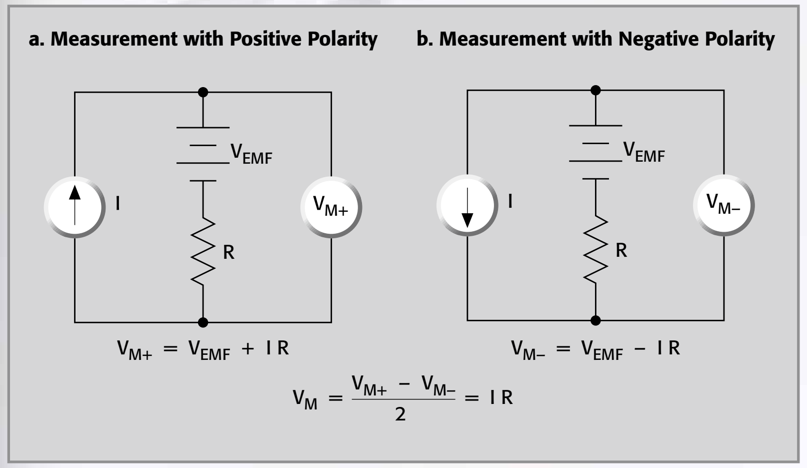


Figure 14: Canceling Thermoelectric EMFs with Current Reversal

For the current-reversal method to be effective, it's important to use a low noise voltmeter with a response speed that is fast compared with the thermal time constant of the circuit under test. If the response speed is too slow, any changes in the circuit temperature during the measurement cycle will cause changes in the thermoelectric EMFs that won't be completely canceled, and some error will result.

DELTA METHOD

When the thermoelectric voltages are constant with respect to the measurement cycle, the current-reversal method will successfully compensate for these offsets. However, if changing thermoelectric voltages are causing inaccurate results, then the delta method should be used. The delta method is similar to the current-reversal method in terms of alternating the current source polarity, but it differs in that it uses three voltage measurements to make each resistance calculation. This method can best be explained through an illustration and mathematical computations.

Figure 15 shows the voltage drop of a DUT as a function of time with an alternating polarity current applied. A voltage measurement (V_{M1}, V_{M2}, V_{M3}, etc.) is taken each time the polarity is changed. Each voltage measurement includes a constant thermal voltage offset (V_{EMF}) and a linearly changing voltage offset (δV). The thermal voltage drift may be approximated as a linear function over short periods, so the rate of change of voltage as a function of time (δV) can also be treated as a constant. The first three voltage measurements include the following voltages:

$$V_{M1} = V_1 + V_{EMF}$$

$$V_{M2} = V_2 + V_{EMF} + \delta V$$

$$V_{M3} = V_3 + V_{EMF} + 2\delta V$$

where: V_{M1}, V_{M2}, and V_{M3} are voltage measurements

V_{M1} is presumed to be taken at time = 0

V_1, V_2, and V_3 are the voltage drop of the DUT due to the applied current

V_{EMF} is the constant thermoelectric voltage offset at the time the V_{M1} measurement is taken

δV is the thermoelectric voltage change

Cancellation of both the thermoelectric voltage offset (V_{EMF}) term and the thermoelectric voltage change (δV) term is possible through mathematical computation using three voltage measurements. First, take one-half the difference of the first two voltage measurements and call this term V_A:

$$V_A = \frac{V_{M1} - V_{M2}}{2} = \frac{(V_1 + V_{EMF}) - (V_2 + V_{EMF} + \delta V)}{2} = \frac{(V_1 - V_2)}{2} - \frac{\delta V}{2}$$

Then, take one-half the difference of the second (V_{M2}) and third (V_{M3}) voltage measurements and call this term V_B:

$$V_B = \frac{V_{M3} - V_{M2}}{2} = \frac{(V_3 + V_{EMF} + 2\delta V) - (V_2 + V_{EMF} + \delta V)}{2} = \frac{(V_3 - V_2)}{2} - \frac{\delta V}{2}$$

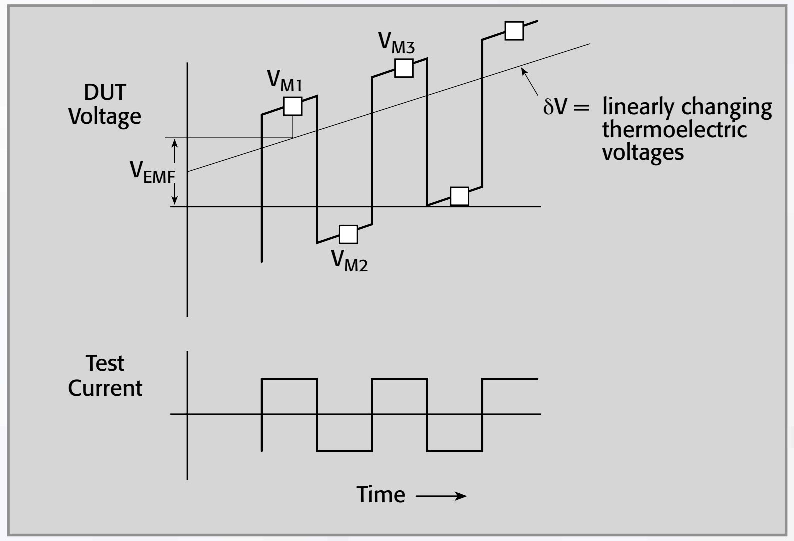
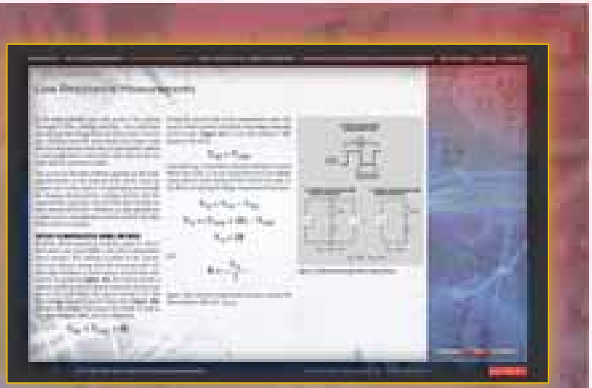


Figure 15: Canceling Thermoelectric EMFs with Delta Method

Both V_A and V_B are affected by the drift in the thermoelectric EMF, but the effect on V_A and V_B is equal and opposite. The final voltage reading is the average of V_A and V_B and is calculated as:

$$V_{FINAL} = \frac{V_A - V_B}{2} = \frac{(V_1 + V_3 - 2V_2)}{4}$$

Notice that both the V_{EMF} and δV terms are canceled out of the final voltage calculation.



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Low Resistance Measurements

In the delta method, each data point is the moving average of three voltage readings. This additional averaging of the voltage measurements means that the data resulting from the delta method has lower noise than the data derived when the current-reversal method is used to calculate it, even when both sets of data are taken over the same time period.

The success of the delta method depends on the linear approximation of the thermal drift, which must be viewed over a short period. Compensating successfully for changing thermoelectric voltages dictates that the measurement cycle time must be faster than the thermal time constant of the DUT. Therefore, an appropriately fast current source and voltmeter must be used for the delta method to be successful.

OFFSET-COMPENSATED OHMS METHOD

Another offset-canceling method used by micro-ohmmeters and many DMMs is the offset-compensated ohms method. This method is similar to the current-reversal method except that the measurements are alternated between a fixed source current and zero current. As shown in **Figure 16a**, the source current is applied to the resistance being measured during only part of the cycle. When the source current is on, the total voltage measured by the instrument (**Figure 16b**) includes the voltage drop across the resistor as well as any thermoelectric EMFs, and it is defined as:

$$V_{M1} = V_{EMF} + IR$$

During the second half of the measurement cycle, the source current is turned off and the only voltage measured by the meter (**Figure 16c**) is any thermoelectric EMF present in the circuit:

$$V_{M2} = V_{EMF}$$

Given that V_{EMF} is accurately measured during the second half of the cycle, it can be subtracted from the voltage measurement made during the first half of the cycle, so the offset-compensated voltage measurement becomes:

$$V_M = V_{M1} - V_{M2}$$

$$V_M = (V_{EMF} + IR) - V_{EMF}$$

$$V_M = IR$$

and,

$$R = \frac{V_M}{1}$$

Again, note that the measurement process cancels the thermoelectric EMF term (V_{EMF}).

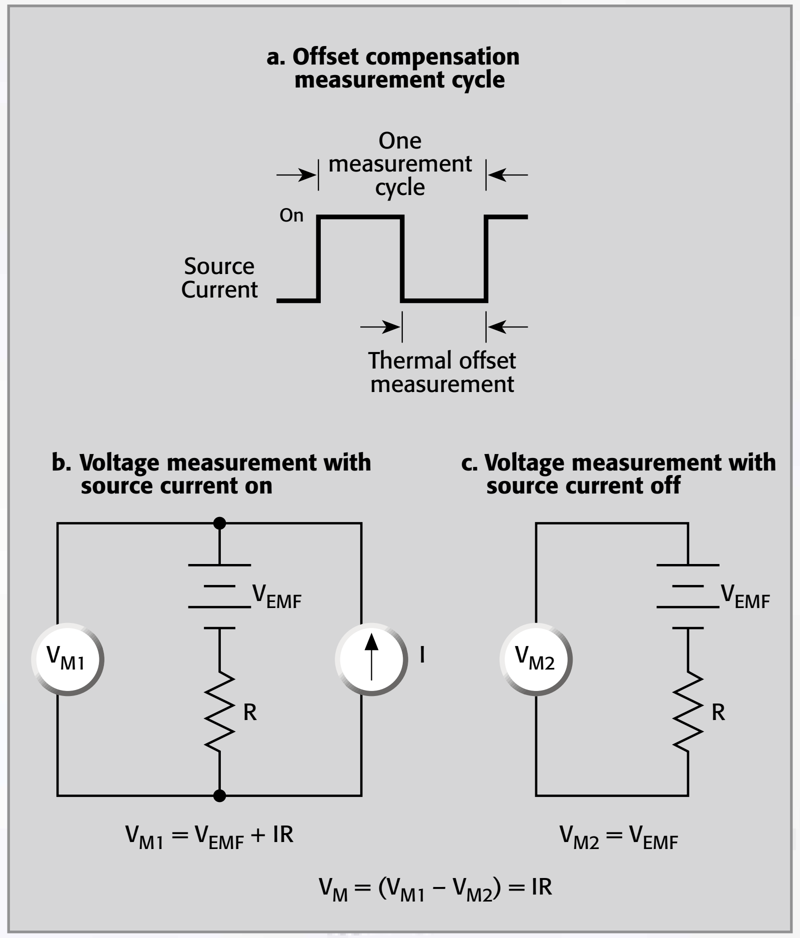

Figure 16: Offset-Compensated Ohms Measurement

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Low Resistance Measurements

Non-Ohmic Contacts

Non-ohmic contacts are evident when the potential difference across the contact isn't linearly proportional to the current flowing through it. Non-ohmic contacts may occur in a low voltage circuit as a result of oxide films or other non-linear connections. A non-ohmic connection is likely to rectify any radio frequency energy (RFI) present, causing an offset voltage to appear in the circuit. There are several ways to check for non-ohmic contacts and methods to reduce them.

If using a micro-ohmmeter or DMM to make low resistance measurements, change the range to check for non-ohmic contacts. Changing the measurement range usually changes the test current as well. A normal condition would indicate the same reading but with higher or lower resolution, depending on whether the instrument was up or down ranged. If the reading is significantly different, this may indicate a non-ohmic condition.

If using a separate current source and voltmeter to make low resistance measurements, each instrument must be checked for non-ohmic contacts. If the current source contacts are non-ohmic, there may be a significant difference in the compliance voltage when the source polarity is reversed. If the voltmeter contacts are non-ohmic, they may rectify any AC pickup present and cause a DC offset error. If this is the case, the offset compensated ohms method is preferred to the current-reversal method for canceling offsets.

To prevent non-ohmic contacts, choose an appropriate contact material, such as indium or gold. Make sure the compliance voltage is high enough to avoid problems due to source contact non-linearity. To reduce error due to voltmeter non-ohmic contacts, use shielding and appropriate grounding to reduce AC pickup.

Device Heating

Device heating can be a consideration when making resistance measurements on temperature-sensitive devices such as thermistors. The test currents used for low resistance measurements are often much higher than the currents used for high resistance measurements, so power dissipation in the device can be a consideration if it is high enough to cause the device's resistance value to change.

Recall that the power dissipation in a resistor is given by this formula:

$$P = I^2R$$

From this relationship, we see that the power dissipated in the device increases by a factor of four each time the current doubles. Thus, one way to minimize the effects of device heating is to use the lowest current possible while still maintaining the desired voltage across the device being tested. If the current cannot be reduced, use a narrow current pulse and a fast responding voltmeter.

Most micro-ohmmeters and DMMs don't have provisions for setting the test current. It is generally determined by the range. In those cases, alternate means must be found to minimize device heating. One simple but effective way to do so is to use the instrument's one-shot trigger mode during measurements. While in this mode, the instrument will apply only a single, brief current pulse to the DUT during the measurement cycle, thereby minimizing errors caused by device heating.

Dry Circuit Testing

Many low resistance measurements are made on devices such as switches, connectors, and relay contacts. If these devices are to be used under "dry circuit" conditions, that is, with an open-circuit voltage less than 20mV and a short-circuit current less than 100mA, the devices should be tested in a manner that won't puncture any oxide film that may have built up on the contacts. If the film is punctured, the measured contact resistance will be lower than if the film remains intact, compromising the validity of the test results.

To avoid oxidation puncture, such measurements are usually made using dry circuit testing, which typically limits the voltage across the DUT to 20mV or less. Some micro-ohmmeters and DMMs have this capability built in, as shown in **Figure 17**. In this micro-ohmmeter, a precision shunt resistor (R_{SH}) is connected across the source terminals to clamp or limit the voltage across the DUT to <20mV. The remaining aspects of the circuit are very similar to the conventional four-wire measurement method: V and R_{REF} make up the current source, which forces current through the unknown resistance (R). This current should be no more than 100mA. The value of the unknown resistance is computed from the sense

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Low Resistance Measurements

voltage (V_M), the voltage across clamping resistor (V_{SH}), the known value of R_{SH}, and the source current.

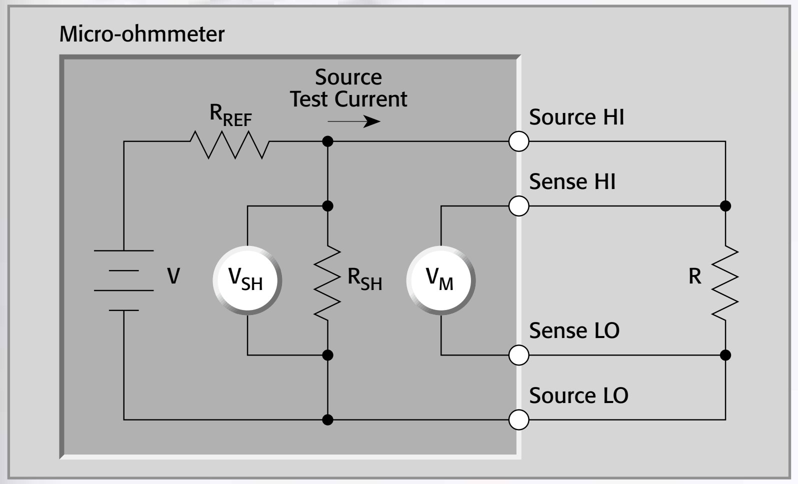


Figure 17: Dry Circuit Testing

If dry circuit testing is to be done with a separate current source and voltmeter, the compliance voltage on the current source must be limited to 20mV or less. If it isn't possible to limit the compliance voltage to this level, a compliance limiting resistor must be used, as shown in **Figure 18**. In this circuit, R_C is the resistor used to limit the voltage to 20mV and R is the unknown resistance.

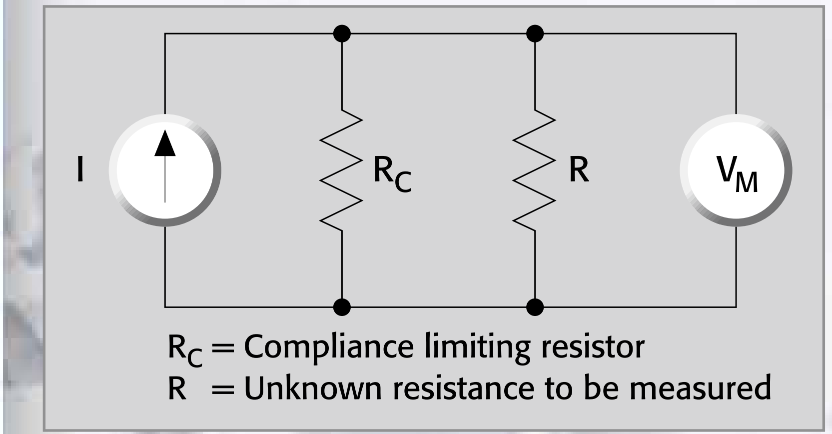


Figure 18: Dry Circuit Testing Using Current Source and Voltmeter

The value of RC must be chosen to limit the voltage at a given test current. For example, if the voltage limit is 20mV and the test current is 200µA, RC can be calculated as:

$$R_C = 20mV/200\mu A = 100\Omega$$

If the unknown resistance (R) is 250mΩ, then R_C will cause a 0.25% error in the measured resistance.

The exact value of the unknown resistance (R) can then be calculated by the following equation:

$$R = \frac{(R_{MEASURED} \times R_C)}{(R_C - R_{MEASURED})}$$

where $R_{MEASURED}$ is the calculated resistance measurement from the measured voltage (V_M) and the source current (I).

Testing Inductive Devices

Inductive devices usually have a small resistance in addition to the inductance. This small resistance is normally measured with a DMM or a micro-ohmmeter. However, the measurements are often difficult because of the interaction between the inductance and the measuring instrument. This is particularly true with high L/R ratios.

Some of the problems that may result include oscillations, negative readings, and generally unstable readings. An oscilloscope picture of an unstable measurement of a 200H inductor is shown in **Figure 19**.

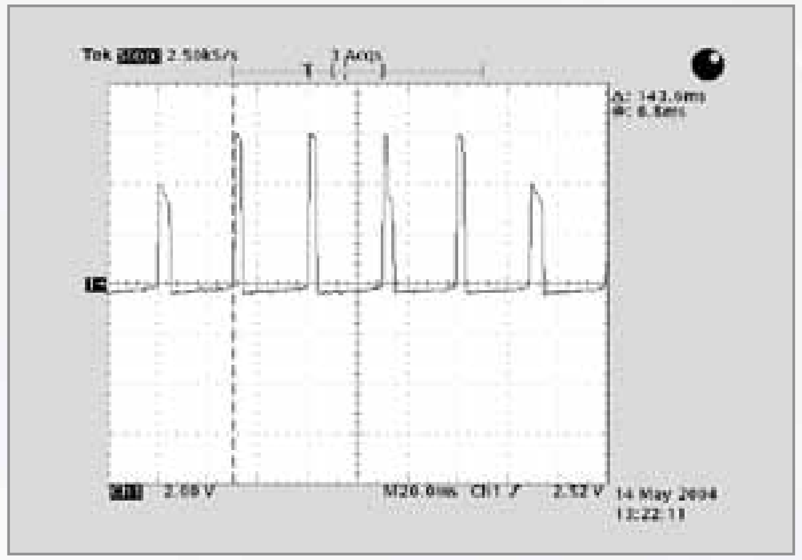


Figure 19: An Unstable Measurement of a 200H Inductor, Acquired with an Oscilloscope

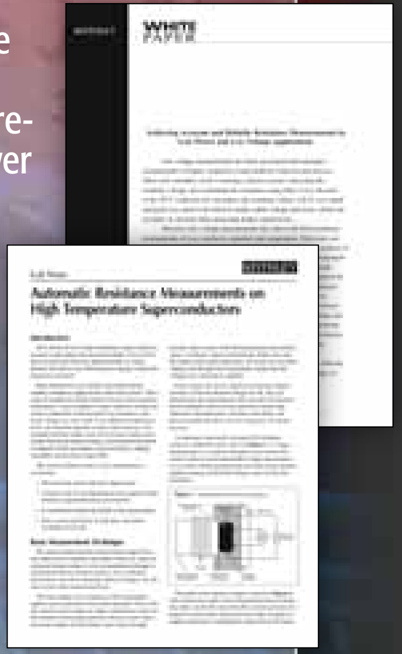
When problems occur, try to take measurements on more than one range and check if the values correspond.

If possible, do not use offset compensation (pulsed current) because inductive reaction to the current pulse may cause unstable measurements or make autoranging difficult. Try using a higher resistance range when possible.

Check for oscillations by connecting an oscilloscope in parallel with the device and the meter. Sometimes, a diode across the inductor may settle down the oscillations by reducing the inductive kick.

FEATURED RESOURCES

- How to Avoid Self-Heating Effects on Nanoscale Devices
- Achieving Accurate and Reliable Resistance Measurements in Low Power and Low Voltage Applications
- Automatic Resistance Measurements on High Temperature Superconductors



ADDITIONAL RESOURCES

- Techniques for Reducing Resistance Measurement Uncertainty: DC Current Reversals vs. Classic Offset Compensation
- Tips for Electrical Characterization of Carbon Nanotubes and Low Power Nanoscale Devices
- Problem: Noisy Readings in Low Resistance Measurements
- Problem: Reading Drift in Low Resistance Measurements

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Low Voltage Application: Hall Effect Measurements

Hall effect measurements have been valuable tools for material characterization since Edwin Hall discovered the phenomenon in 1879. Essentially, the Hall effect can be observed when the combination of a magnetic field through a sample and a current along the length of the sample creates an electrical current perpendicular to both the magnetic field and the current, which in turn creates a transverse voltage that is perpendicular to both the magnetic field and the current (**Figure 20**).

Figure 20: Illustration of Hall effect

Today, Hall effect measurements are used in many phases of the electronics industry, from basic materials research and device development to device manufacturing. A Hall effect measurement system is useful for determining a variety of material parameters, but the primary one is the Hall voltage (V_H). Other important parameters such as carrier mobility, carrier concentration (n), Hall coefficient (R_H), resistivity, magnetoresistance (R_B), and the conductivity type (N or P) are all derived from the Hall voltage measurement.

Hall effect measurements are useful for characterizing virtually every material used in producing semiconductors, such as silicon (Si) and germanium (Ge), as well as most compound semiconductor materials, including silicon-germanium (SiGe), silicon-carbide (SiC), gallium arsenide (GaAs), aluminum gallium arsenide (AlGaAs), indium arsenide (InAs), indium gallium arsenide (InGaAs), indium phosphide (InP), cadmium telluride (CdTe), and mercury cadmium telluride (HgCdTe). They're often used in characterizing thin films of these materials for solar cells/photovoltaics, as well as organic semiconductors and nano-materials like graphene. They are equally useful for characterizing both low resistance materials (metals, transparent oxides, highly doped semiconductor materials, high temperature superconductors, dilute magnetic semiconductors, and GMR/TMR materials used in disk drives) and high resistance semiconductor materials, including semi-insulating GaAs, gallium nitride (GaN), and cadmium telluride (CdTe).

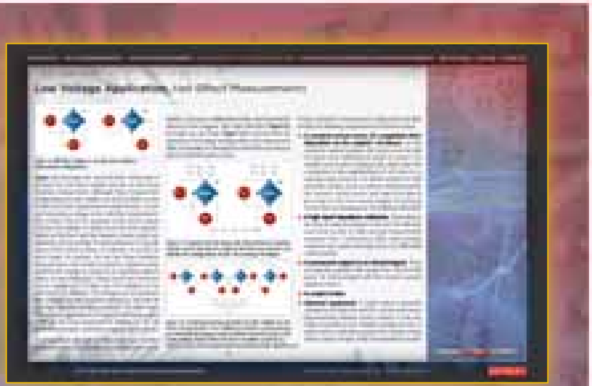
Hall effect measurements were first routinely used in the semiconductor industry more than two decades ago, when scientists and researchers needed tools for characterizing bulk silicon materials. However, once the bulk mobility of silicon was well understood, Hall effect measurements were no longer considered critical. But today's semiconductor materials are not just silicon–manufacturers often add germanium to silicon in the strain lattice to get higher mobility. Moreover, modern semiconductor materials are no longer bulk materials–they're often in the form of thin films, such as those used in copper indium gallium diselenide (CIGS) and CdTe solar cells. As a result, IC manufacturers now have to go back to determining carrier concentration and carrier mobility independently, applications for which Hall effect measurements are ideal.

MEASURING MOBILITY USING HALL EFFECT TECHNIQUES

The first step in determining carrier mobility is to measure the Hall voltage (V_H) by forcing both a magnetic field perpendicular to the sample and a current through the sample. The combination of the current flow (I) and the magnetic field (B) causes a transverse current. The resulting potential (V_H) is measured across the device. Accurate measurements of both the sample thickness (t) and its resistivity (ρ) are also required. The resistivity can be determined using either a four-point probe or van der Pauw measurement technique. With just these five parameters (B, I, V_H, t, and ρ), the Hall mobility can be calculated using this formula:

$$\mu_H = \frac{|V_H t|}{BI\rho}$$

Because Hall voltages are typically quite small (millivolts or less), as is the measured van der Pauw resistivity, the right measurement and averaging techniques are critical to obtaining accurate mobility results when using this formula.



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Low Voltage Application: Hall Effect Measurements

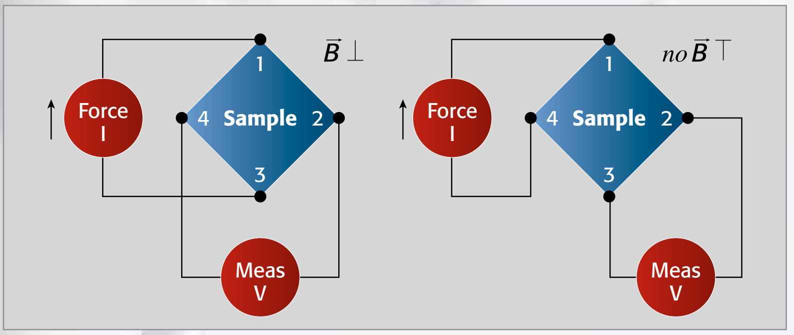

Figure 21. Hall effect voltage vs. van der Pauw resistance measurement configurations

Figure 21 illustrates the measurement configurations for both the Hall effect voltage and the van der Pauw resistivity measurement. Although these measurement configurations are very similar in as much as both use four contacts and both measurements involve forcing a current and measuring a voltage, in the Hall effect measurement, the current is forced on opposite nodes of the sample and then the voltage is measured on the other opposite nodes so the force and the measure contact points are interlaced and the voltage for semiconductors is typically around KT/q, which is about 25 millivolts. It can also be much lower. In contrast, for van der Pauw resistivity measurements, the current is forced on adjacent nodes and then the voltage is measured on opposing adjacent nodes so everything that is being forced and measured is on nearest pins; in that case, the voltages can be well above 20 millivolts. The voltages can be anywhere from millivolts for low resistivity materials to 100 volts for very high resistivity insulating materials. The other major differentiator is that there is no magnetic field being applied in the van der Pauw measurement, whereas for the Hall effect measurement, a transverse magnetic field is applied.

To obtain results with high confidence, the recommended technique involves a combination of reversing source current polarity, sourcing on additional terminals, and reversing the direction of the magnetic field. Eight Hall effect (**Figure22**) and eight van der Pauw (**Figure 23**) measurements are performed. If the voltage readings within each measurement differ substantially, it's advisable to recheck the test setup to look for potential sources of error.

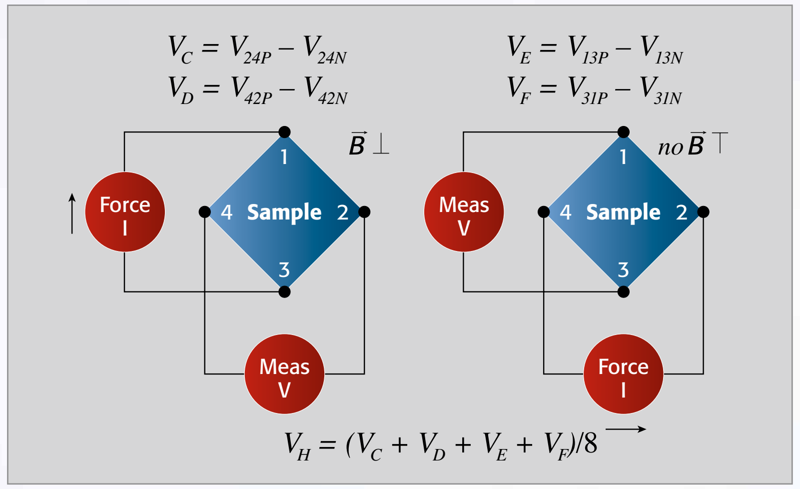

Figure 22: Compute the Hall voltage with both positive and negative polarity current and with the magnetic field both up and down, and with the two configurations shown. Then average all voltages.

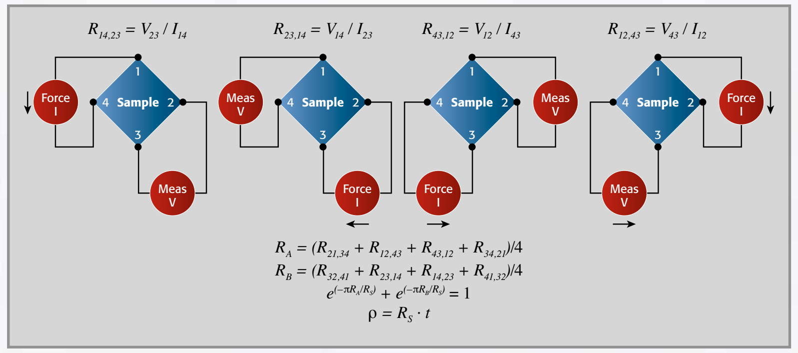

Figure 23: Computing average resistivity (ñ) with multiple van der Pauw measurements. Four additional resistance measurements are made with the source current polarity reversed in each of the configurations shown. If $R_A = R_B$, then R simplifies to pRA/ln(2). Reference http://www.nist.gov/eeel/semiconductor/hall_algorithm.cfm.

A basic Hall effect measurement configuration will likely include the following components and optional extras:

- **A constant-current source of a magnitude that's dependent on the sample's resistance.** For low resistivity material samples, the source must be able to output from milliamps to amps of current. For samples such as semi-insulating GaAs, which may have a resistivity in the neighborhood of 10^7 ohm·cm, a sourcing range as low as 1nA will be needed. For high resistivity samples (such as intrinsic semiconductors), the constant current source may have to be able to go as low as 1nA, but a source capable of producing current from 10 microamps to 100 milliamps will suffice.
- **A high input impedance voltmeter.** Depending on the level of material resistivity under test, the voltmeter used must be able to make accurate measurements anywhere from 1 microvolt to 100V. High resistivity materials may require ultra-high input Z or differential measurements.
- **A permanent magnet or an electromagnet.** These are typically available with ranges from 500 to 5000 gauss. An electromagnet will also require a power supply to drive it.
- **A sample holder.**
- **Optional equipment.** A switch matrix is generally included to eliminate the need for manual connections/disconnections between probe contacts; it may also make it possible to test multiple samples at once. A switch matrix is definitely required if the sample is being held in a liquid nitrogen dewar for temperature studies.

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Low Voltage Application: Hall Effect Measurements

Hall mobility is highly dependent on sample temperature, so it's often desirable to monitor this temperature, particularly if the application involves repeating measurements each time the sample's temperature is adjusted. Many test configurations include a temperature-measuring probe; for high accuracy work, the probe's resolution should be about 0.1° Celsius. A prober chuck that can either heat or cool the sample and a temperature controller are generally necessary for on-wafer measurements when doing temperature studies. A cryostat is necessary to hold the sample in the liquid nitrogen bath for low temperature studies.

For making on-wafer measurements of numerous devices, a prober with a manipulator and probe tips will likely be essential.

The most appropriate Hall effect measurement configuration for a particular application is based in large part on the sample's total resistance as measured by the electrical test equipment. This total resistance is the sum of the sample resistance and the contact resistance, that is, the resistance between the sample and the electrical contacts to it. The sample resistance depends on the sample's intrinsic resistivity, which is expressed in units of ohm-centimeters (ohm·cm), and its thickness.

Each resistance range has different measurement requirements and the type and number of components of the systems needed to test them can vary significantly. To illustrate the configuration process, here's an example of a configuration appropriate for the widest range of sample resistances, from 1 micro-ohm to 1 terra-ohm. A configuration of this type would be most appropriate for those characterizing thin-film photovoltaic materials, those who are studying the effects of doping concentration on an intrinsic semiconductor, or those studying the effects of doping polymers with increasing amounts of carbon nanotubes.

The system configuration illustrated in **Figure 24** is appropriate for the widest range of sample resistances, from 1 micro-ohm to 1 terra-ohm. It employs Keithley's special matrix switching card optimized for Hall effect measurements, the Model 7065, housed in a Model 7001 Switch Mainframe. This card buffers test signals from the sample to the measurement instrumentation and switches current from the current source to the sample. The Model 7065 card offers the advantage of unity gain buffers that can be switched in and out to allow the measurement of high resistances by buffering the sample resistance from the meter.

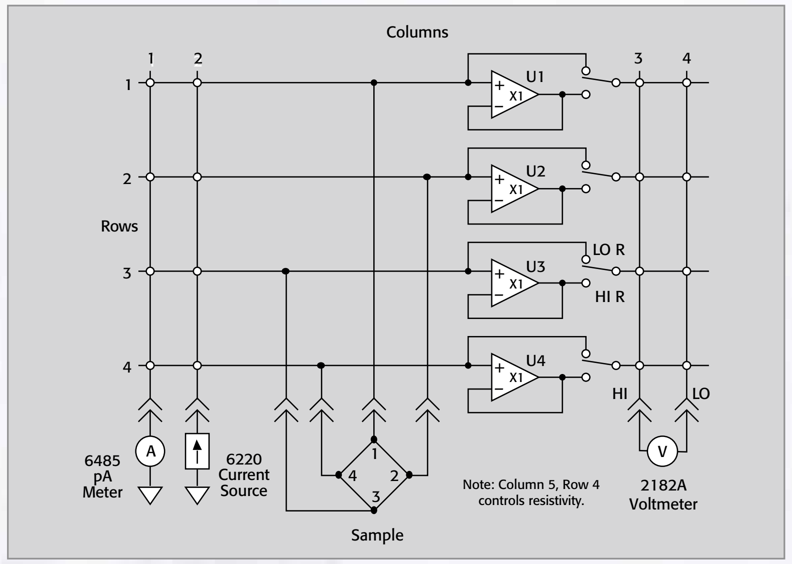
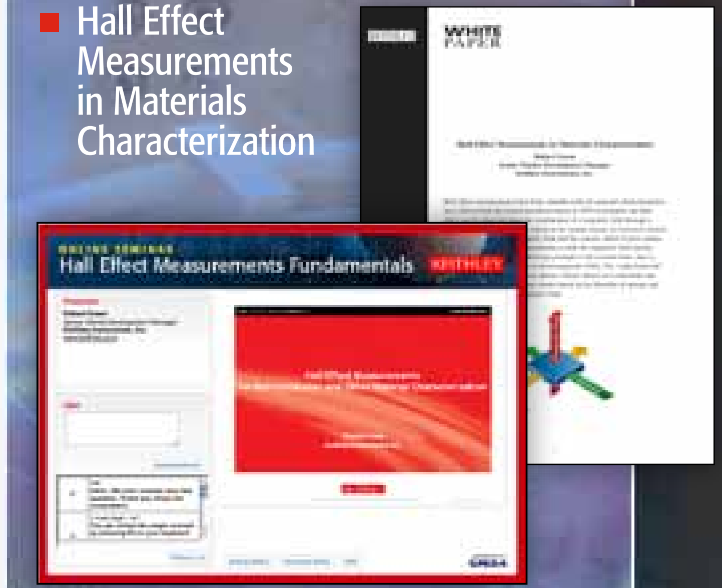


Figure 24: Example test configuration for characterizing materials with wide range of sample resistances (1 micro-ohm to 1 tera-ohm)

The test setup also includes the Model 6485 Picoammeter, the Model 6220 DC Current Source, and the Model 2182A Nanovoltmeter. The Model 6485 Picoammeter is included to measure leakage currents so they can either be subtracted out or monitored to make sure they aren't impacting the high resistance measurement. The Model 6220 and the Model 2182A are designed to work together seamlessly, using a delta mode technique to synchronize their operation and optimize their performance. Essentially, the delta mode automatically triggers the current source to alternate the signal polarity, then triggers a nanovoltmeter reading at each polarity, cancelling out both constant and drifting thermoelectric offsets, and ensuring the results reflect the true value of the voltage. Once the Model 6220 and the Model 2182A are connected properly, all it takes to start a test is pressing the current source's Delta button and then the Trigger button. The Model 2182A also provides a second channel of voltage measurement capability, which is useful for monitoring the temperature of the sample. Although the Model 6220 serves as the constant current source in the configuration shown, substituting the Model 6221 AC+DC Current Source, which has a built-in arbitrary waveform generator, has the advantage of allowing users to make AC Hall effect measurements. For applications for which it is acceptable to trade off the low resistance capability of the system shown to reduce the system cost (i.e., to provide just mid-range to high resistance capability), a Model 2000 Digital Multimeter can be substituted for the Model 2182A Nanovoltmeter.

FEATURED RESOURCES

- Hall Effect Measurements in Materials Characterization



- Hall Effect Measurement Fundamentals webinar

ADDITIONAL RESOURCES

- Precision, Low Current Sources for Device Testing and Characterization
- Low-Level Pulsed Electrical Characterization with the Model 6221/2182A Combination

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Low-Resistance Application: Superconductor Resistance Measurements

At extremely low temperatures, some metals and alloys lose their resistance to electrical current and become superconductive. A superconductor's transition temperature and critical current density are two commonly measured parameters. The superconducting transition temperature is the point at which a material's resistance changes from a finite value to zero. The critical current density is the maximum current density a material can carry under specific temperature and magnetic field conditions before it becomes resistive. The higher these two parameters are, the better the superconductor is. Determining these two parameters requires measuring very small resistances, so a nanovoltmeter and a programmable current source are essential for precision measurements.

Figure 25 shows a basic superconductor resistance measurement test system using the combination of a Model 2182A Nanovoltmeter and a Model 6220 Current Source for measuring the resistance. The voltage leads should be made of a material with a low Seebeck coefficient with respect to the sample. The sensitivity of the Model 2182A Nanovoltmeter is crucial to obtaining precision measurements because the application demands the ability to measure extremely low voltages.

For transition temperature measurements, the current source must be kept below the critical current of the sample. If the current becomes too high, the power dissipated may damage the sample and the cryostat. For critical current measurements, however, the current source must be able to exceed the critical current of the sample. If that means that more than 100mA is needed (the current the Model 6220 Current Source can provide), a Model 2440 5A Current Source may be an appropriate solution. The current source should have programmable polarity, so the test can be performed using the current-reversal method.

The resistance is measured using the same techniques employed in low voltage and low resistance measurements. It is essential to use a four-wire measurement technique because it eliminates lead resistance by forcing a current through the sample with one pair of leads while measuring the voltage drop with a second pair of leads. In addition, the Delta method is essential to eliminate the effects of changing thermoelectric EMFs, which may interfere with measurement accuracy.

The Delta method consists of measuring the voltage drop across the material with the current in one direction, then reversing the polarity of the current source and taking a second voltage measurement. Three voltage measurements are used to calculate each resistance value. In cases where hysteresis, non-linearity, or asymmetry is apparent, the current can be varied from one value to another of the same polarity. This will provide the average resistance between these two currents.

The Model 2182A Nanovoltmeter and Model 6220 Current Source work together to implement the Delta method automatically. In this mode, the Model 6220 automatically alternates the polarity, then triggers the nanovoltmeter to take a reading at each polarity. Then, the Model 6220 displays the "compensated" resistance value. As shown in **Figure 26**, the resistance can be plotted vs. temperature as the sample temperature is changing.

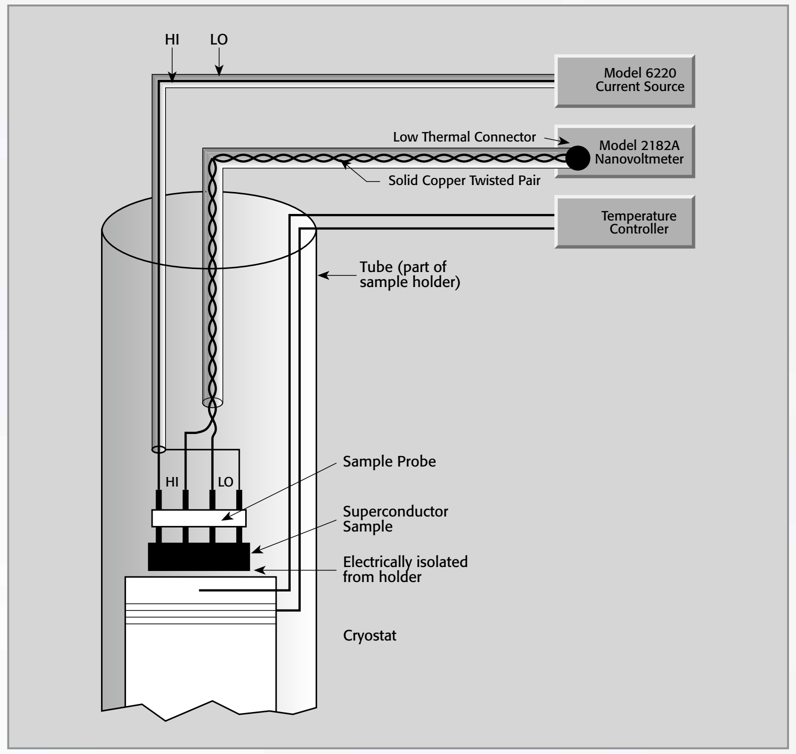

Figure 25: Superconductor Resistance Test System

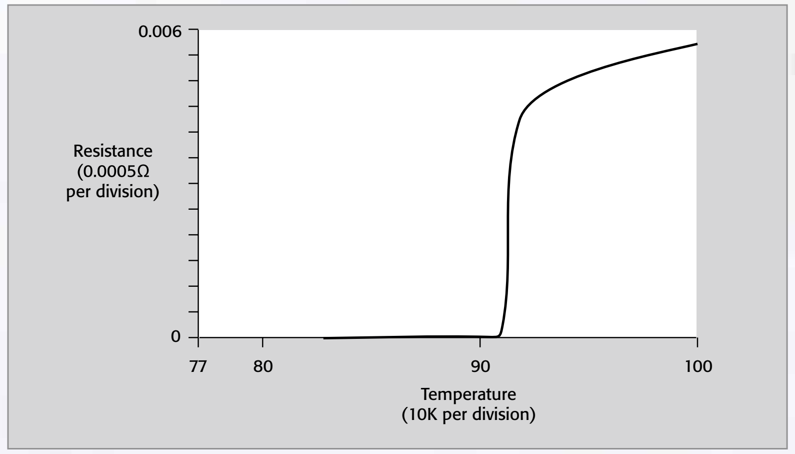

Figure 26: Resistance vs. Temperature of Superconductor

For determining the critical current, the Model 2182A and Model 6220 Current Source can be used together to produce a precision I-V curve over a range of currents.

FEATURED RESOURCES

- Automatic Resistance Measurements on High Temperature Superconductors

- Determining Resistivity and Conductivity Type using a Four-Point Collinear Probe and the Model 6221 Current Source

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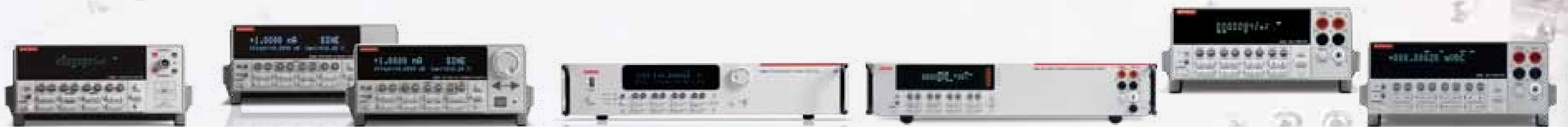
Selector Guide: Low Voltage/Low Resistance Meters



Model	2182A	6220/6221	3706	2750	2010	2002
VOLTAGE RANGE (Full Scale)						
From	10 mV	N/A	100 mV	100 mV	100 mV	200 mV
To	100 V	N/A	300 V	1000 V	1000 V	1000 V
Input Voltage Noise	1.2 nV rms	N/A	100 nV rms	<1.5 µV rms	100 nV rms	150 nV rms
CURRENT RANGE						
From	N/A	100 fA DC (also 2 pA peak AC, 6221 only)	N/A	N/A	N/A	N/A
To	N/A	±105 mA DC (also 100 mA peak AC, 6221 only)	N/A	N/A	N/A	N/A
RESISTANCE RANGE						
From[1]	10 nΩ[3]	10 nΩ (when used with 2182A)	0.9 mΩ	0.4 mΩ	0.9 mΩ	1.2 mΩ
To[2]	100 MΩ[3]	100 MΩ (when used with 2182A)	100 MΩ	100 MΩ	100 MΩ	1 GΩ
THERMOCOUPLE TEMPERATURE						
From	–200°C	N/A	–150°C	–200°C	–200°C	–200°C
To	1820°C	N/A	1820°C	1820°C	1372°C	1820°C
FEATURES						
IEEE-488	•	•	•	•	•	•
RS-232	•	•		•	•	•
CE	•	•	•	•	•	•
Input Connection	Special low thermoelectric w/copper pins. Optional 2187-4 Modular Probe Kit adds banana plugs, spring clips, needle probes, and alligator clips.	Trigger Link, Digital I/O, Ethernet	Rear panel 15 pin D-SUB. Optional accessories: 3706-BAN, 3706-BKPL, 3706-TLK	Banana jacks (4)	Banana jacks (4)	Banana jacks (4)
Special Features	Delta mode and differential conductance with Model 6220 or 6221. Pulsed I-V with Model 6221. Analog output. IEEE-488. RS-232.	Controls Model 2182A for low-power resistance and I-V measurements.	Dry circuit. Offset compensation. Plug-in switch/relay modules. USB. LXI Class B/Ethernet. Digital I/O.	Dry circuit. Offset compensation. DMM. IEEE-488. RS-232. Digital I/O. Plug-in modules.	Dry circuit. Offset compensation. DMM. IEEE-488. RS-232. Plug-in scanner cards.	8½ digits. DMM. Plug-in scanner cards.

NOTES

1. Lowest resistance measurable with better than 10% accuracy.
2. Highest resistance measurable with better than 1% accuracy.
3. Delta mode, offset voltage compensation with external current source. 10nΩ if used with 5A test current with Model 2440.

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Absolute Accuracy. A measure of the closeness of agreement of an instrument reading compared to that of a primary standard having absolute traceability to a standard sanctioned by a recognized standards organization. Accuracy is often separated into gain and offset terms. *See also* **Relative Accuracy.**

A/D (Analog-to-Digital) Converter. A circuit used to convert an analog input signal into digital information. All digital meters use an A/D converter to convert the input signal into digital information.

Analog Output. An output that is directly proportional to the input signal.

Assembler. A molecular manufacturing device that can be used to guide chemical reactions by positioning molecules. An assembler can be programmed to build virtually any molecular structure or device from simpler chemical building blocks.

Auto-Ranging. The ability of an instrument to automatically switch among ranges to determine the range offering the highest resolution. The ranges are usually in decade steps.

Auto-Ranging Time. For instruments with auto-ranging capability, the time interval between application of a step input signal and its display, including the time for determining and changing to the correct range.

Bandwidth. The range of frequencies that can be conducted or amplified within certain limits. Bandwidth is usually specified by the –3dB (half-power) points.

Bias Voltage. A voltage applied to a circuit or device to establish a reference level or operating point of the device during testing.

Capacitance. In a capacitor or system of conductors and dielectrics, that property which permits the storage of electrically separated charges when potential differences exist between the conductors. Capacitance is related to the charge and voltage as follows: $C = Q/V$, where C is the capacitance in farads, Q is the charge in coulombs, and V is the voltage in volts.

Carbon Nanotube. A tube-shaped nanodevice formed from a sheet of single-layer carbon atoms that has novel electrical and tensile properties. These fibers may exhibit electrical conductivity as high as copper, thermal conductivity as high as diamond, strength 100 times greater than steel at one-sixth of steel's weight, and high strain to failure. They can be superconducting, insulating, semiconducting, or conducting (metallic). Non-carbon nanotubes, often called nanowires, are often created from boron nitride or silicon.

Channel (switching). One of several signal paths on a switching card. For scanner or multiplexer cards, the channel is used as a switched input in measuring circuits, or as a switched output in sourcing circuits. For switch cards, each channel's signals paths are independent of other channels. For matrix cards, a channel is established by the actuation of a relay at a row and column crosspoint.

Coaxial Cable. A cable formed from two or more coaxial cylindrical conductors insulated from each other. The outermost conductor is often earth grounded.

Common-Mode Rejection Ratio (CMRR). The ability of an instrument to reject interference from a common voltage at its input terminals with respect to ground. Usually expressed in decibels at a given frequency.

Common-Mode Current. The current that flows between the input low terminal and chassis ground of an instrument.

Common-Mode Voltage. A voltage between input low and earth ground of an instrument.

Contact Resistance. The resistance in ohms between the contacts of a relay or connector when the contacts are closed or in contact.

Contamination. Generally used to describe the unwanted material that adversely affects the physical, chemical, or electrical properties of a semiconductor or insulator.

D/A (Digital-to-Analog) Converter. A circuit used to convert digital information into an analog signal. D/A converters are used in many instruments to provide an isolated analog output.

Dielectric Absorption. The effect of residual charge storage after a previously charged capacitor has been discharged momentarily.

Digital Multimeter (DMM). An electronic instrument that measures voltage, current, resistance, or other electrical parameters by converting the analog signal to digital information and display. The typical five-function DMM measures DC volts, DC amps, AC volts, AC amps, and resistance.

Drift. A gradual change of a reading with no change in input signal or operating conditions.

Dry Circuit Testing. The process of measuring a device while keeping the voltage across the device below a certain level (e.g., <20mV) in order to prevent disturbance of oxidation or other degradation of the device being measured.

Electrochemical Effect. A phenomenon whereby currents are generated by galvanic battery action caused by contamination and humidity.

Electrometer. A highly refined DC multimeter. In comparison with a digital multimeter, an electrometer is characterized by higher input resistance and greater current sensitivity. It can also have functions not generally available on DMMs (e.g., measuring electric charge, sourcing voltage).

EMF. Electromotive force or voltage. EMF is generally used in context of a voltage difference caused by electromagnetic, electrochemical, or thermal effects.

Electrostatic Coupling. A phenomenon whereby a current is generated by a varying or moving voltage source near a conductor.

Error. The deviation (difference or ratio) of a measurement from its true value. True values are by their nature indeterminate. *See also* **Random Error** *and* **Systematic Error**.

Fall Time. The time required for a signal to change from a large percentage (usually 90%) to a small percentage (usually 10%) of its peak-to-peak value. *See also* **Rise Time**.

Faraday Cup. A Faraday cup (sometimes called a Faraday cage or icepail) is an enclosure made of sheet metal or mesh. It consists of two electrodes, one inside the other, separated by an insulator. While the inner electrode is connected to the electrometer, the outer electrode is connected to ground. When a charged object is placed inside the inner electrode, all the charge will flow into the measurement instrument. The electric field inside a closed, empty conductor is zero, so the cup shields the object placed inside it from any atmospheric or stray electric fields. This allows measuring the charge on the object accurately.

Feedback Picoammeter. A sensitive ammeter that uses an operational amplifier feedback configuration to convert an input current into voltage for measurement.

Floating. The condition where a common-mode voltage exists between an earth ground and the instrument or circuit of interest. (Circuit low is not tied to earth potential.)

Four-Point Probe. The four-point collinear probe resistivity measurement technique involves bringing four equally spaced probes in contact with the material of unknown resistance. The array is placed in the center of the material. A known current is passed through the two outside probes and the voltage is sensed at the two inside probes. The resistivity is calculated as follows:

$$\rho = \frac{\pi}{\ln 2} \times \frac{V}{I} \times t \times k$$

where: V = the measured voltage in volts, I = the source current in amps, t = the wafer thickness in centimeters, k = a correction factor based on the ratio of the probe to wafer diameter and on the ratio of wafer thickness to probe separation.

Four-Terminal Resistance Measurement. A measurement where two leads are used to supply a current to the unknown, and two different leads are used to sense the voltage drop across the resistance. The four-terminal configuration provides maximum benefits when measuring low resistances.

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Fullerene. Refers to C60, an approximately spherical, hollow, carbon molecule containing 60 carbon atoms arranged in interlocking hexagons and pentagons, reminiscent of the geodesic dome created by architect R. Buckminster Fuller. Sometimes called "buckminsterfullerene" or "buckyball."

Ground Loop. A situation resulting when two or more instruments are connected to different points on the ground bus and to earth or power line ground. Ground loops can develop undesired offset voltages or noise.

Guarding. A technique that reduces leakage errors and decreases response time. Guarding consists of a conductor driven by a low impedance source surrounding the lead of a high impedance signal. The guard voltage is kept at or near the potential of the signal voltage.

Hall Effect. The measurement of the transverse voltage across a conductor when placed in a magnetic field. With this measurement, it is possible to determine the type, concentration, and mobility of carriers in silicon.

High Impedance Terminal. A terminal where the source resistance times the expected stray current (for example, 1μA) exceeds the required voltage measurement sensitivity.

Input Bias Current. The current that flows at the instrument input due to internal instrument circuitry and bias voltage.

Input Impedance. The shunt resistance and capacitance (or inductance) as measured at the input terminals, not including effects of input bias or offset currents.

Input Offset Current. The difference between the two currents that must be supplied to the input measuring terminals of a differential instrument to reduce the output indication to zero (with zero input voltage and offset voltage). Sometimes informally used to refer to input bias current.

Input Offset Voltage. The voltage that must be applied directly between the input measuring terminals, with bias current supplied by a resistance path, to reduce the output indication to zero.

Input Resistance. The resistive component of input impedance.

Insulation Resistance. The ohmic resistance of insulation. Insulation resistance degrades quickly as humidity increases.

Johnson Noise. The noise in a resistor caused by the thermal motion of charge carriers. It has a white noise spectrum and is determined by the temperature, bandwidth, and resistance value.

Leakage Current. Error current that flows (leaks) through insulation resistance when a voltage is applied. Even high resistance paths between low current conductors and nearby voltage sources can generate significant leakage currents.

Long-Term Accuracy. The limit that errors will not exceed during a 90-day or longer time period. It is expressed as a percentage of reading (or sourced value) plus a number of counts over a specified temperature range.

Maximum Allowable Input. The maximum DC plus peak AC value (voltage or current) that can be applied between the high and low input measuring terminals without damaging the instrument.

MEMS. Microelectromechanical systems. Describes systems that can respond to a stimulus or create physical forces (sensors and actuators) and that have dimensions on the micrometer scale. They are typically manufactured using the same lithographic techniques used to make silicon-based ICs.

Micro-ohmmeter. An ohmmeter that is optimized for low resistance measurements. The typical micro-ohmmeter uses the four-terminal measurement method and has special features for optimum low level measurement accuracy.

Molecular Electronics. Any system with atomically precise electronic devices of nanometer dimensions, especially if made of discrete molecular parts, rather than the continuous materials found in today's semiconductor devices.

Molecular Manipulator. A device combining a proximal-probe mechanism for atomically precise positioning with a molecule binding site on the tip; can serve as the basis for building complex structures by positional synthesis.

Molecular Manufacturing. Manufacturing using molecular machinery, giving molecule-by-molecule control of products and by-products via positional chemical synthesis.

Molecular Nanotechnology. Thorough, inexpensive control of the structure of matter based on molecule-by-molecule control of products and by-products; the products and processes of molecular manufacturing, including molecular machinery.

MOSFET. A metal oxide field effect transistor. A unipolar device characterized by extremely high input resistance.

Nano-. A prefix meaning one billionth (1/1,000,000,000).

Nanoelectronics. Electronics on a nanometer scale. Includes both molecular electronics and nanoscale devices that resemble current semiconductor devices.

Nanotechnology. Fabrication of devices with atomic or molecular scale precision. Devices with minimum feature sizes less than 100 nanometers (nm) are considered products of nanotechnology. A nanometer [one-billionth of a meter (10^{-9}m)] is the unit of length generally most appropriate for describing the size of single molecules.

Nanovoltmeter. A voltmeter optimized to provide nanovolt sensitivity (generally uses low thermoelectric EMF connectors, offset compensation, etc.).

Noise. Any unwanted signal imposed on a desired signal.

Normal-Mode Rejection Ratio (NMRR). The ability of an instrument to reject interference across its input terminals. Usually expressed in decibels at a specific frequency such as that of the AC power line.

Normal-Mode Voltage. A voltage applied between the high and low input terminals of an instrument.

Offset Current. A current generated by a circuit even though no signals are applied. Offset currents are generated by triboelectric, piezoelectric, or electrochemical effects present in the circuit.

Overload Protection. A circuit that protects the instrument from excessive current or voltage at the input terminals.

Picoammeter. An ammeter optimized for the precise measurement of small currents. Generally, a feedback ammeter.

Piezoelectric Effect. A term used to describe currents generated when mechanical stress is applied to certain types of insulators.

Precision. Refers to the freedom of uncertainty in the measurement. It is often applied in the context of repeatability or reproducibility and should not be used in place of accuracy. *See also* Uncertainty.

Quantum Dot. A nanoscale object (usually a semiconductor island) that can confine a single electron (or a few) and in which the electrons occupy discrete energy states, just as they would in an atom. Quantum dots have been called "artificial atoms."

Random Error. The mean of a large number of measurements influenced by random error matches the true value. *See also* Systematic Error.

Range. A continuous band of signal values that can be measured or sourced. In bipolar instruments, range includes positive and negative values.

Reading. The displayed number that represents the characteristic of the input signal.

Reading Rate. The rate at which the reading number is updated. The reading rate is the reciprocal of the time between readings.

Relative Accuracy. The accuracy of a measuring instrument in reference to a secondary standard. *See also* Absolute Accuracy.

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Repeatability. The closeness of agreement between successive measurements carried out under the same conditions.

Reproducibility. The closeness of agreement between measurements of the same quantity carried out with a stated change in conditions.

Resolution. The smallest portion of the input (or output) signal that can be measured (or sourced) and displayed.

Response Time. For a measuring instrument, the time between application of a step input signal and the indication of its magnitude within a rated accuracy. For a sourcing instrument, the time between a programmed change and the availability of the value at its output terminals. *Also known as* Settling Time.

Rise Time. The time required for a signal to change from a small percentage (usually 10%) to a large percentage (usually 90%) of its peak-to-peak amplitude. *See also* Fall Time.

Sensitivity. The smallest quantity that can be measured and displayed.

Settling Time. For a measuring instrument, the time between application of a step input signal and the indication of its magnitude within a rated accuracy. For a sourcing instrument, the time between a programmed change and the availability of the value at its output terminals. Also known as Response Time.

Shielding. A metal enclosure around the circuit being measured, or a metal sleeve surrounding the wire conductors (coax or triax cable) to lessen interference, interaction, or leakage. The shield is usually grounded or connected to input LO.

Shunt Ammeter. A type of ammeter that measures current by converting the input current into a voltage by means of shunt resistance. Shunt ammeters have higher voltage burden and lower sensitivity than do feedback ammeters.

Shunt Capacitance Loading. The effect on a measurement of the capacitance across the input terminals, such as from cables or fixtures. Shunt capacitance increases both rise time and settling time.

Short-Term Accuracy. The limit that errors will not exceed during a short, specified time period (such as 24 hours) of continuous operation. Unless specified, no zeroing or adjustment of any kind are permitted. It is expressed as percentage of reading (or sourced value) plus a number of counts over a specified temperature range.

Single Electron Transistor. A switching device that uses controlled electron tunneling to amplify current. An SET is made from two tunnel junctions that share a common electrode. A tunnel junction consists of two pieces of metal separated by a very thin (~1nm) insulator. The only way for electrons in one of the metal electrodes to travel to the other electrode is to tunnel through the insulator. Tunneling is a discrete process, so the electric charge that flows through the tunnel junction flows in multiples of e, the charge of a single electron.

Source Impedance. The combination of resistance and capacitive or inductive reactance the source presents to the input terminals of a measuring instrument.

Source-Measure Unit (SMU). An electronic instrument that sources and measures DC voltage and current. Generally, SMUs have two modes of operation: source voltage and measure current, or source current and measure voltage. Also known as source-monitor unit or stimulus-measurement unit.

SourceMeter. A SourceMeter instrument is very similar to the source-measure unit in many ways, including its ability to source and measure both current and voltage and to perform sweeps. In addition, a SourceMeter instrument can display the measurements directly in resistance, as well as voltage and current. It is designed for general-purpose, high speed production test applications. It can also be used as a source for moderate to low level measurements and for research applications.

Source Resistance. The resistive component of source impedance. *See also* Thevenin Equivalent Circuit.

Spintronics. Electronics that take advantage of the spin of an electron in some way, rather than just its charge.

Standard Cell. An electrochemical cell used as a voltage reference in laboratories.

Superconductor. A conductor that has zero resistance. Such materials usually become superconducting only at very low temperatures.

Switch Card. A type of card with independent and isolated relays for switching inputs and outputs on each channel.

Switching Mainframe. A switching instrument that connects signals among sourcing and measuring instruments and devices under test. A mainframe is also referred to as a scanner, multiplexer, matrix, or programmable switch.

Systematic Error. The mean of a large number of measurements influenced by systematic error deviates from the true value. *See also* Random Error.

Temperature Coefficient. A measure of the change in reading (or sourced value) with a change in temperature. It is expressed as a percentage of reading (or sourced value), plus a number of counts per degree change in temperature.

Temperature Coefficient of Resistance. The change of resistance of a material or device per degree of temperature change, usually expressed in ppm/°C.

Thermoelectric EMFs. Voltages resulting from temperature differences within a measuring circuit or when conductors of dissimilar materials are joined together.

Thevenin Equivalent Circuit. A circuit used to simplify analysis of complex, two-terminal linear networks. The Thevenin equivalent voltage is the open-circuit voltage and the Thevenin equivalent resistance equals the open-circuit voltage divided by the short-circuit current.

Transfer Accuracy. A comparison of two nearly equal measurements over a limited temperature range and time period. It is expressed in ppm. *See also* Relative Accuracy, Short-Term Accuracy.

Triboelectric Effect. A phenomenon whereby currents are generated by charges created by friction between a conductor and an insulator.

Trigger. An external stimulus that initiates one or more instrument functions. Trigger stimuli include: an input signal, the front panel, an external trigger pulse, and IEEE-488 bus X, talk, and GET triggers.

Two-Terminal Resistance Measurement. A measurement where the source current and sense voltage are applied through the same set of test leads.

Uncertainty. An estimate of the possible error in a measurement; in other words, the estimated possible deviation from its actual value.

van der Pauw Measurement. A measurement technique used to measure the resistivity of arbitrarily shaped samples.

Voltage Burden. The voltage drop across the input terminals of an ammeter.

Voltage Coefficient. The change in resistance value with applied voltage. Usually expressed in percent/V or in ppm/V.

Warm-up Time. The time required after power is applied to an instrument to achieve rated accuracy at reference conditions.

Zero Offset. The reading that occurs when the input terminals of a measuring instrument are shorted (voltmeter) or open-circuited (ammeter).

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BELGIUM
Sint-Pieters-Leeuw
Ph: 02-3630040
Fax: 02-3630064
info@keithley.nl
www.keithley.nl

CHINA
Beijing
Ph: 86-10-8447-5556
Fax: 86-10-8225-5018
china@keithley.com
www.keithley.com.cn

FRANCE
Saint-Aubin
Ph: 01-64532020
Fax: 01-60117726
info@keithley.fr
www.keithley.fr

GERMANY
Germering
Ph: 089-84930740
Fax: 089-84930734
info@keithley.de
www.keithley.de

INDIA
Bangalore
Ph: 091-80-30792-600, -726 (dir)
Fax: 091-80-30792-688
support_india@keithley.com
www.keithley.com

ITALY
Peschiera Borromeo (Mi)
Ph: 02-5538421
Fax: 02-55384228
info@keithley.it
www.keithley.it

JAPAN
Tokyo
Ph: 81-3-5733-7555
Fax: 81-3-5733-7556
info.jp@keithley.com
www.keithley.jp

KOREA
Seoul
Ph: 82-2-574-7778
Fax: 82-2-574-7838
keithley@keithley.co.kr
www.keithley.co.kr

MALAYSIA
Penang
Ph: 60-4-643-9679
Fax: 60-4-643-3794
sea@keithley.com
www.keithley.com

NETHERLANDS
Son
Ph: 040-2675-506, -502
or call the UK
Fax: 040-2675-509
info@keithley.nl
www.keithley.nl

SINGAPORE
Singapore
Ph: 65-6747-9077
Fax: 65-6747-2991
sea@keithley.com
www.keithley.com

SWITZERLAND
Brugg
Ph: 056-460-78-90
Fax: 056-460-78-79
info@keithley.ch
www.keithley.ch

TAIWAN
Hsinchu
Ph: 886-3-572-9077
Fax: 886-3-572-9031
info_tw@keithley.com
www.keithley.com.tw

UNITED KINGDOM
Theale
Ph: 0118-9297500
Fax: 0118-9297519
info@keithley.co.uk
www.keithley.co.uk

For all countries not listed contact the KIEX department in Germany: Keithley Instruments GmbH/KIEX. Ph: +49-89-84 93 07-62. Fax: +49-89-84 93 07-85. E-Mail: kiex@keithley.com

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