Technical Information

Low Voltage/Low Resistance Measurements

How to Select a Voltmeter

Many kinds of instruments can measure voltage, including digital multimeters (DMMs), electrometers, and nanovoltmeters. Making voltage measurements successfully requires a voltmeter with significantly higher input impedance than the internal impedance (source impedance) of the device under test (DUT). Without it, the voltmeter will measure less potential difference than existed before the voltmeter was connected. Electrometers have very high input impedance (typically in the order of 100TΩ [10^{14}Ω]), so they're the instrument of choice for high impedance voltage measurements. DMMs and nanovoltmeters can typically be used for measuring voltages from 10MΩ sources or lower. Nanovoltmeters are appropriate for measuring low voltages (microvolts or less) from low impedance sources.

Low Voltage Measurements

Significant errors may be introduced into low voltage measurements by offset voltage and noise sources that can normally be ignored when measuring higher signal levels. Steady offsets can generally be nulled out by shorting the ends of the test leads together, then enabling the instrument's zero (relative) feature. The following paragraphs discuss non-steady types of error sources that can affect low voltage measurement accuracy and how to minimize their impact on the measurements.

Thermoelectric EMFs

The most common sources of error in low voltage measurements are thermoelectric voltages (thermoelectric EMFs) generated by temperature differences between junctions of conductors (**Figure 1**).

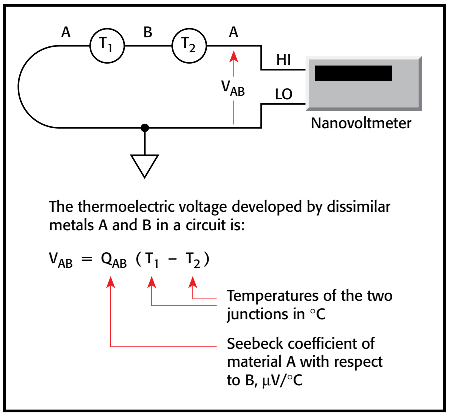

Figure 1. Thermoelectric EMFs

Constructing circuits using the same material for all conductors minimizes thermoelectric EMF generation. For example, connections made by crimping copper sleeves or lugs on copper wires results in cold-welded copper-to-copper junctions, which generate minimal thermoelectric EMFs. Also, connections must be kept clean and free of oxides.

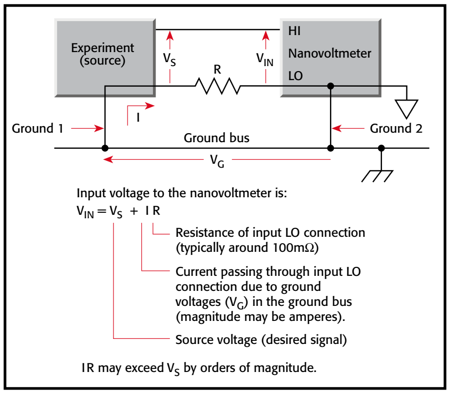

Figure 2a. Multiple grounds (ground loops)

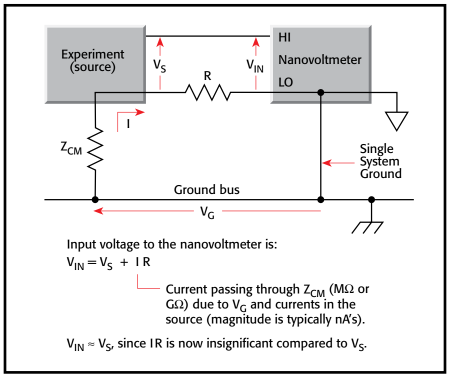

Figure 2b. Single system ground

Minimizing temperature gradients within the circuit also reduces thermoelectric EMFs. A way to minimize such gradients is to place all junctions in close proximity and provide good thermal coupling to a common, massive heat sink. If this is impractical, thermally couple *each pair* of corresponding junctions of dissimilar materials to minimize their temperature differentials which will also help minimize the thermoelectric EMFs.

Johnson Noise

The ultimate limit to how well the voltmeter can resolve a voltage is defined by Johnson (thermal) noise. This noise is the voltage associated with the motion of electrons due to their thermal energy. All sources of voltage will have internal resistance and thus produce Johnson noise. The noise voltage developed by any resistance can be calculated from the following equation:

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

k = Boltzmann's constant (1.38×10^{-23} J/K)

T = absolute temperature of the source in Kelvin

B = noise bandwidth in Hz

R = resistance of the source in ohms

From this equation, it can be observed that Johnson noise may be reduced by lowering the temperature and by decreasing the bandwidth of the measurement. Decreasing the bandwidth of the measurement is equivalent to increasing the response time of the instrument; thus, *in addition to increasing filtering*, the bandwidth can be reduced by increasing instrument integration (typically in multiples of power line cycles).

Ground Loops

When both the signal source and the measurement instrument are connected to a common ground bus, a ground loop is created (**Figure 2a**). This is the case when, for instance, a number of instruments are plugged into power strips on different instrument racks. Frequently, there is a difference in potential between the ground points. This potential difference—even though it may be small—can cause large currents to circulate and create unexpected voltage drops. The cure for ground loops is to ground the entire measurement circuit at only one point. The easiest way to accomplish this is to isolate the DUT (source) and find a single, good earth-ground point for the measuring system, as shown in **Figure 2b**. Avoid grounding sensitive measurement circuits to the same ground system used by other instruments, machinery, or other high power equipment.

Magnetic Fields

Magnetic fields generate spurious 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 (**Figure 3a**). Changing magnetic fields 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.

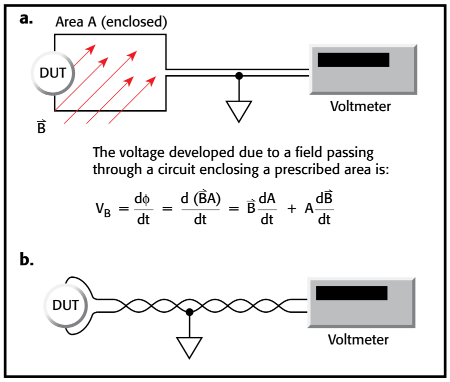

Figure 3. Minimizing interference from magnetic fields with twisted leads

To minimize induced magnetic voltages, leads must be run close together and should be tied down to minimize movement. Twisted pair cabling reduces the effects of magnetic fields in two ways: first, it reduces the loop area through which the magnetic

Low Voltage/Low Resistance Measurements

field is interfering; second, a magnetic field will create voltages of opposite polarities for neighboring loops of the twisted pair that will cancel each other. (**Figure 3b**)

Low Resistance Measurements

Low resistances (<10Ω) are typically best measured by sourcing current and measuring voltage. For very low resistances (micro-ohms or less) or where there are power limitations involved, this method will require measuring very low voltages, often using a nanovoltmeter. Therefore, all the low voltage techniques and error sources described previously also apply here. Low resistance measurements are subject to additional error sources. The next sections describe methods to minimize some of these.

Lead Resistance and Four-Wire Method

Resistance measurements in the normal range (>10Ω) are generally made using the two-wire method shown in **Figure 4a**. The main problem with the two-wire method for low resistance measurements (<10Ω) is the error caused by lead resistance. The voltage measured by the meter will be the sum of the voltage directly across the test resistance and the voltage drop across the leads. Typical lead resistances lie in the range of 1mΩ to 100mΩ. Therefore, the four-wire (Kelvin) connection method shown in **Figure 4b** is preferred for low resistance measurements. In this configuration, the test current is forced through the DUT through one set of test leads while the voltage is measured using a second set of leads called the sense leads. There is very little current running through the sense leads, so the sense lead resistance has effectively been eliminated.

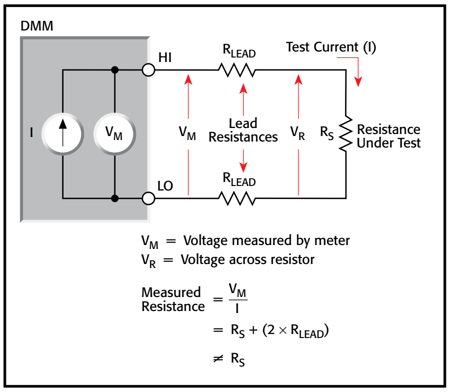

Figure 4a. Two-wire resistance measurement: Lead resistance error

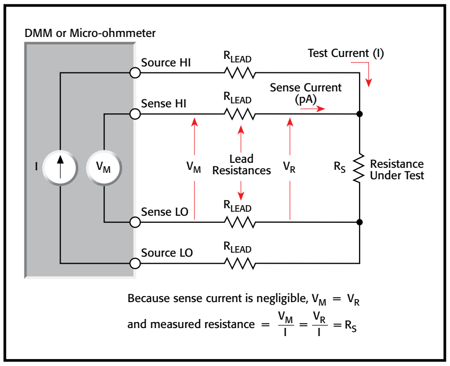

Figure 4b. Four-wire resistance measurement

Thermoelectric EMFs

Thermoelectric voltages can seriously affect low resistance measurement accuracy. Given that resistance measurements involve *controlling* the current through the DUT, there are ways to overcome these unwanted offsets in addition to those mentioned in the low voltage measurement section, namely, the offset-compensated ohms method and the current-reversal method.

- **Offset Compensation Technique** (**Figure 5a**) applies a source current to the resistance being measured only for part of the measurement cycle. When the source current is on, the total voltage measured by the instrument is the sum of the voltage due to the test current and any thermoelectric EMFs present in the circuit. During the second half of the measurement cycle, the source current is turned off and the only voltage measured is that due to the thermoelectric EMF. This unwanted offset voltage can now be subtracted from the voltage measurement made during the first half of the delta mode cycle.
- With the Offset Compensation technique, the source current is decided by the instrument. To characterize at a specific current or a variety of currents, the Current Reversal technique/Two-step Delta technique (described below) will provide more flexibility.
- **Current Reversal Technique/Two-Step Delta Technique** (**Figure 5b**)
- Thermoelectric EMFs can also be cancelled by taking two voltages with test currents of opposite polarity. The voltage due to the test current can now be calculated using the formula shown in **Figure 5b**. This method provides 2× better signal-to-noise ratio and, therefore, better accuracy than the offset compensation technique. (*This is the method employed by the Model 2182A Nanovoltmeter/Model 622x Current Source combination.*)

For these methods to be effective, the consecutive measurements need to be made rapidly when compared with the thermal time constant of the circuit under test. If the instruments' response speed is too low, changes in the circuit temperature during the measurement cycle will cause changes in the thermoelectric EMFs, with the result that the thermoelectric EMFs are no longer fully cancelled.

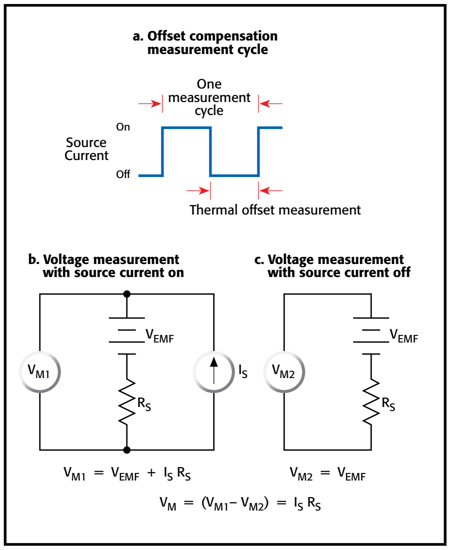

Figure 5a. Subtracting thermoelectric EMFs with Offset Compensation

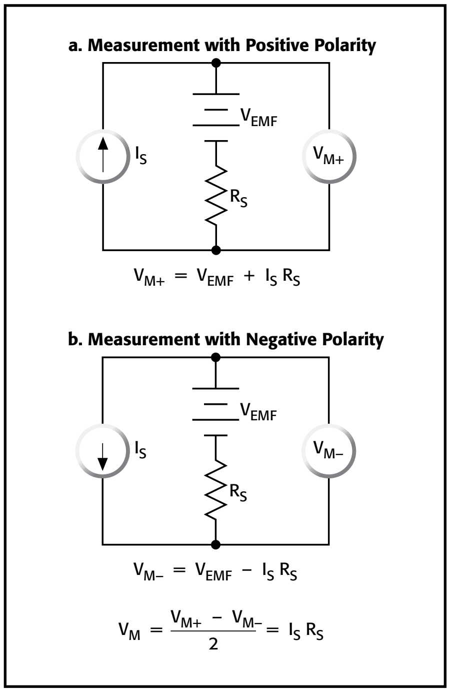

Figure 5b. Canceling thermoelectric EMFs with Current Reversal

Three-Step Delta Technique

The three-step delta technique eliminates errors due to changing thermoelectric voltages (offsets and drifts) and significantly reduces white noise. This results in more accurate low resistance measurements (or more accurate resistance measurements of any type when it is necessary to apply very low power to DUTs that have limited power handling capability). This technique offers three advantages over the two-step delta technique.

A delta reading is a pair of voltage measurements made at a positive test current and a negative test current. Both the two-step and three-step delta techniques can cancel *constant* thermoelectric voltage by alternating the test current. The three-step technique can also cancel *changing* thermoelectric voltages by alternating the current source three times to make two delta measurements: one at a negative-going step and one at a positive going step. This eliminates errors caused by changing thermoelectric EMFs 10× better than the two-step technique (**Figure 6**).

The three-step technique provides accurate voltage readings of the intended signal unimpeded by thermoelectric offsets and drifts only if the current source alternates quickly and the voltmeter makes accurate voltage measurements within a short time interval. The Model 622x Current Source paired with the Model 2182A Nanovoltmeter is optimized for this application. These products implement the three-step technique in a way that offers better white noise immunity than the two-step technique by spending over 90% of its time performing measurements. In addition, the three-step technique is faster, providing 47 readings/second to support a wider variety of applications. Interestingly, the formula used for the three-step technique is identical to that used for differential conductance (**Figure 10**).

Pulsed, Low Voltage Measurements

Short test pulses are becoming increasingly important as modern electronics continue to shrink in size. Short pulses mean less power put into the DUT. In very small devices, sometimes even a small amount of power is enough to destroy them. In other devices, a small amount of power could raise the temperature significantly, causing the measurements to be invalid.

With superconducting devices, a small amount of heat introduced while making measurements can raise the device temperature and alter the results. When sourcing current and measuring voltage, the sourced current dissipates heat (I^2R) into the device and leads. With the lowest resistance devices (<10$\mu\Omega$), the power dissipated during the measurement may be primarily at contact points, etc., rather than in the device itself. It is important to complete the measurement before this heat can be conducted to the device itself, so fast pulsed measurements are critical even at these lowest resistances.

With higher resistance devices, significant power is dissipated within the device. Therefore, with these devices, it is even more important to reduce the measurement power by reducing the source current or the source pulse width. Many tests measure device properties across a range of currents, so reducing the current is not usually an option. Shorter pulses are the only solution.

The Model 6221 Current Source was designed with microsecond rise times on all ranges to enable short pulses. The Model 2182A Nanovoltmeter offers a low latency trigger, so that a measurement can begin as little as 10μs after the Model 6221 pulse has been applied. The entire pulse, including a complete nanovolt measurement, can be as short as 50μs. In addition, all pulsed measurements of the 6221/2182A are line synchronized. This line synchronization, combined with the three-step delta technique, causes all 50/60Hz noise to be rejected (**Figure** 7).

Dry Circuit Testing

Applications that involve measuring contact resistance may require that existing oxide layers remain unbroken during the measurement. This can be done by limiting the test current to less than 100mA and the voltage drop across the sample to no more than 20mV. Most low resistance meters have this "dry circuit" measurement technique built in.

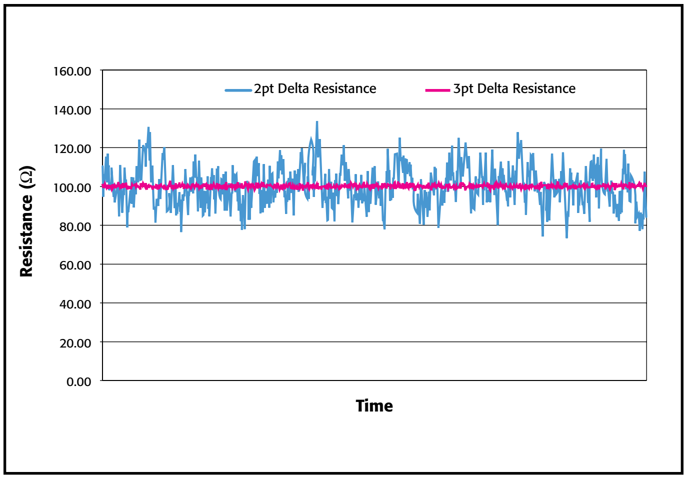

Figure 6. 1000 delta resistance readings using 100Ω resistor and 10nA source current.

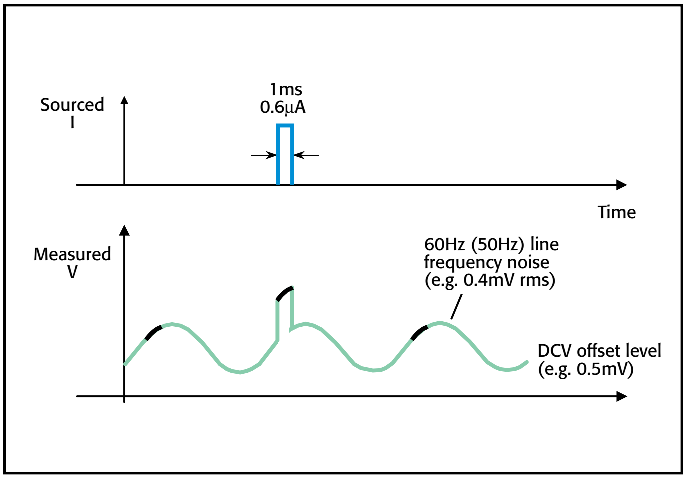

Figure 7. Operating at low voltage levels, measurements are susceptible to line frequency interference. Using line synchronization eliminates line frequency noise.

Resistance Measurements on the Nanoscale

Nanovolt Level Resistance Measurements

In the macroscopic world, conductors may have obeyed Ohm's Law (**Figure 8a**), but in the nanoscale, Ohm's definition of resistance is no longer relevant (**Figure 8b**). Because the slope of the I-V curve is no longer a fundamental constant of the material, a detailed measurement of the slope of that I-V curve at every point is needed to study nanodevices. This plot of differential conductance (dG = dI/dV) is the most important measurement made on small scale devices, but presents a unique set of challenges.

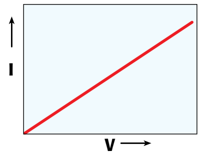

Figure 8a. Macroscopic scale (Classical)

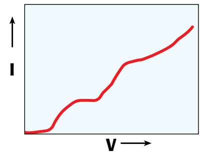

Figure 8b. Nanoscale (Quantum)

Differential conductance measurements are performed in many areas of research, though sometimes under different names, such as: electron energy spectroscopy, tunneling spectroscopy, and density of states. The fundamental reason that differential conductance is interesting is that the conductance reaches a maximum at voltages (or more precisely, at electron energies in eV) at which the electrons are most active. This explains why dI/dV is directly proportional to the density of states and is the most direct way to measure it.

Existing Methods of Performing Differential Conductance

The I-V Technique:

The I-V technique performs a current-voltage sweep (I-V curve) and takes the mathematical derivative. This technique is simple, but noisy. It only requires one source and one measurement instrument, which makes it relatively easy to coordinate and control. The fundamental problem is that even a small amount of noise becomes a large noise when the measurements are differentiated (**Figure 9**). To reduce this noise, the I-V curve and its derivative must be measured repeatedly. Noise will be reduced by $\sqrt{N}$, where N is the number of times the curve is measured.

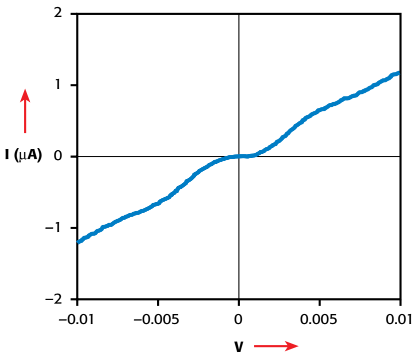

Figure 9a. I-V curve

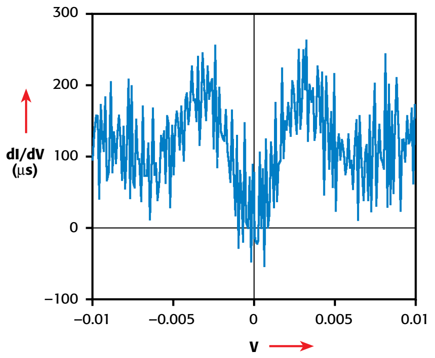

Figure 9b. Differentiated I-V curve. True dI/dV curve obscured by noise.

The AC Technique:

The AC technique superimposes a low amplitude AC sine wave on a stepped DC bias to the sample. It then uses lock-in amplifiers to obtain the AC voltage across and AC current through the DUT. The problem with this method is that while it provides a small improvement in noise over the I-V curve technique, it imposes a large penalty in system complexity, which includes precise coordination and computer control of six to eight instruments. Other reasons for the complexity of the system include the challenges of mixing the AC signal and DC bias, of ground loops, and of common mode current noise.

Keithley has developed a new technique that is both simple and low noise: the four-wire, Source Current–Measure Voltage technique.

Four-Wire, Source Current – Measure Voltage Technique

Now there is another approach to differential conductance. This technique is performed by adding an alternating current to a linear staircase sweep. The amplitude of the alternating portion of the current is the differential current, dI (**Figure 10**). The differential current is constant throughout the test. After the voltage is measured at each current step, the delta voltage between consecutive steps is calculated. Each delta voltage is averaged with the previous delta voltage to calculate the differential voltage, dV. The differential conductance, dG, can now be derived using dI/dV. This technique requires only one measurement sweep when using the Model 2182A Nanovoltmeter and a Model 622x Current Source, so it is faster, quieter, and simpler than any previous method.

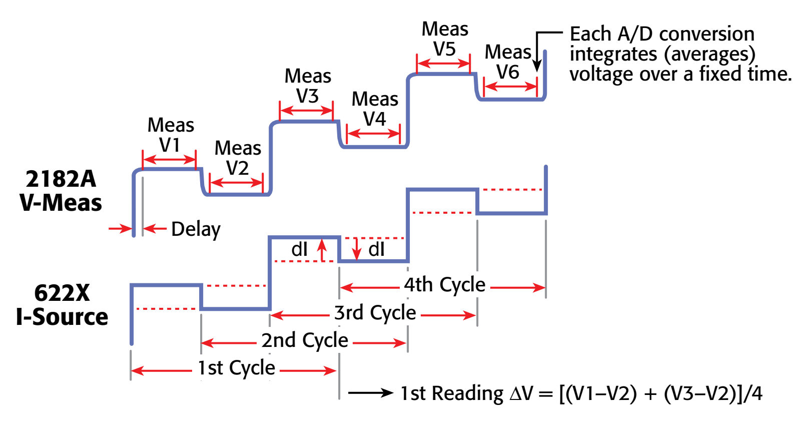

Figure 10. Detail of applied current and measured device voltage