KEITHLEY

Application Note Series

Number 312

High Resistance Measurements

Introduction

Resistance is most often measured with a digital multimeter, which can make measurements up to about 200MΩ. However, in some cases, resistances in the gigohm and higher ranges must be measured accurately. These cases include such applications as characterizing high megohm resistors, determining the resistivity of insulators and measuring the insulation resistance of printed circuit boards. These measurements are made by using an electrometer, which can measure both very low current and high impedance voltage. Using an electrometer, resistances up to $10^{18}\Omega$ can be measured depending on the method used. One method is to source voltage and measure current and the other method is to source current and measure voltage. Besides using the proper method and instrumentation, special measurement techniques such as shielding and guarding must be used to minimize leakage current, noise and other undesirable effects that can degrade the accuracy of the measurements.

Measurement Methods

Two methods are used to measure high resistance, the constant voltage method and the constant current method. In the constant-voltage method, a known voltage is sourced and a picoammeter or electrometer ammeter is used to measure the resulting current. In the constant current method, a constant current is forced through the unknown resistance and the voltage drop across the resistance is measured.

Constant Voltage Method

The basic configuration of the constant voltage method is shown in ***Figure 1***. In this method, a constant voltage source, V, is placed in series with the unknown resistor, R, and an electrometer ammeter, A. Since the voltage drop across an electrometer ammeter is negligible, essentially all the voltage appears across R. The resulting current is measured by the ammeter and the resistance is calculated using Ohm's law, R=V/I.

To make these measurements, an electrometer or picoammeter and a constant voltage source are required. The sensitivity of the electrometer is much better than 1pA. Some electrometers and picoammeters have a constant voltage source built into the instrument, such as the Model 6517A Electrometer/High Resistance Meter and the Model 487 Picoammeter/Voltage Source. In addition, the Model 6430 Sub-Femtoamp Remote SourceMeter® instrument offers both constant voltage and constant current sources so that either the constant voltage or the constant current method can be used to measure high resistance.

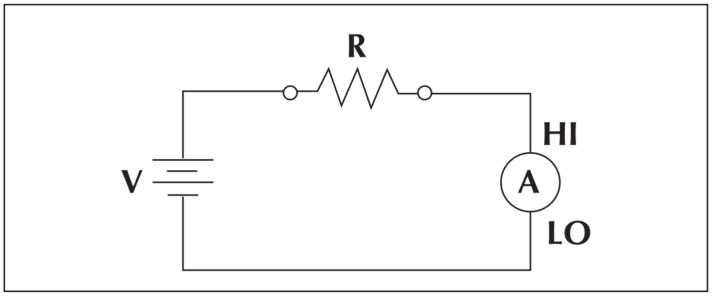

Figure 1: The constant voltage method for measuring resistance

For accurate measurements, the high impedance terminal of the ammeter is always connected to the high impedance point of the circuit being measured. If not, erroneous measurements may result.

Some of the applications which use this method include: testing two-terminal high resistance devices, measuring insulation resistance, and determining the volume and surface resistivity of insulating materials.

Testing Two-Terminal Devices

Applications such as voltage coefficient testing of resistors and leakage resistance measurements of capacitors are examples of high resistance measurements on two-terminal devices. These measurements are set up as shown in ***Figure 1***. The device should be placed in a shielded test fixture to prevent errors due to electrostatic interference. Care must be taken to avoid touching the body of the component so it does not become contaminated with body oils.

These measurements are often dependent on the applied voltage and/or time. For example, high megohm resistors often exhibit a change in resistance with a change in the applied voltage. This change is known as the voltage coefficient.

An example of a time dependent measurement is the leakage resistance of capacitors. The capacitor must be allowed to charge fully by the applied voltage before the measurement is made. Otherwise, an erroneous current of a much higher value will be measured. The time period during which the capacitor is charging is referred to as the "soak" period. A typical soak period is seven time constants which would allow for 0.1% of the final value.

Insulation Resistance Measurements

Insulation resistance, IR, is the ratio of a DC applied voltage to a specimen between two electrodes and the total current between them. The two electrodes are either embedded into or in contact with the specimen. The insulation resistance is dependent on both the surface and volume resistance of the material. The DC voltage is applied for a specified period of time before the resulting current is measured.

This test procedure is described in detail in the American Society for Testing Materials method D257 titled, "DC Resistance or Conductance of Insulating Materials." According to this procedure, an applied voltage of 500V is applied for 60 seconds and then the resulting current is measured. This time and voltage often varies depending upon the application but must always be consistent to a specific test in order to make accurate comparisons.

Sometimes the insulation resistance of a sample is measured only to determine if it is an open circuit. If this is the case, the value of what is considered to be an open circuit must be defined. For example, any resistance value above 100GΩ may be considered an open circuit. The accuracy of the measurement is not important, but only that it is above a certain value.

Examples of insulation resistance measurements include measuring the leakage between traces on a printed circuit board or the resistance between conductors in a multiconductor cable. Because IR measurements usually involve multiple conductors, a switching system is often required to switch the picoammeter and source to all the conductors in the test circuit. Keithley has a line of scanner products that can switch low currents without degrading accuracy.

Volume and Surface Resistivity Measurements

Volume resistivity is the electrical resistance through a one-centimeter cube of insulating material and is expressed in ohm-centimeters. Surface resistivity is the electrical resistance between two electrodes on the surface of an insulating material and is expressed in ohms (usually stated as ohms per square). Both volume and surface resistivity measurements are obtained by taking resistance measurements and then converting them to resistivity values by taking geometric considerations into account.

To account for the geometry, electrodes with convenient dimensions should be used, such as the Keithley 8008 or 8009 Resistivity Chamber. These electrodes are made of stainless steel and follow the ASTM D257 standard. The basic measurement techniques for the volume and surface resistivity measurements using the 8008 and 8009 are shown in ***Figure 2***. The volume resistivity is measured by applying a voltage across the sample and measuring the resulting current. The resistivity is calculated from the geometry of the electrodes and the thickness of the sample. The surface resistivity is measured by applying a voltage across the surface of the sample, between the bottom two electrodes. The resulting current is measured and the resistivity is calculated. The recommended sample size for these fixtures is three to four inches in diameter and between 0.001 and 0.125 inch thick. The ASTM procedure also describes several other electrode configurations, depending on the size and shape of the specimen.

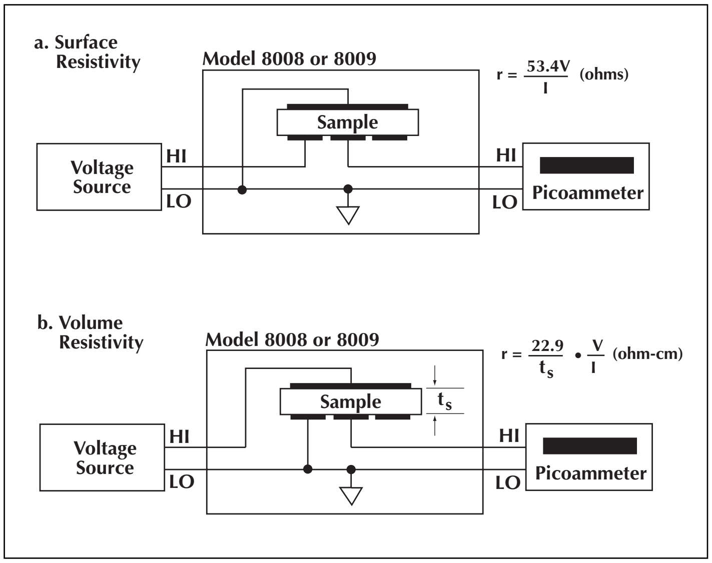

Figure 2: Resistivity measurements

If the sample is made of rigid material, such as glass epoxy or ceramic, and the electrodes are rigid, conductive rubber may be needed to make a better contact between the electrodes and the surface of the material. The Model 8009 Resistivity Chamber includes conductive rubber for the top and bottom electrodes.

Like insulation resistance, volume and surface resistance measurements are also dependent on the applied voltage and time. Humidity will also affect the results of the surface resistance measurements. Too much moisture will cause the resistance measurements to be lower than normal.

Constant Current Method

The basic configuration for the constant current method is shown in ***Figure 3***. Current from the constant current source, I, flows through the unknown resistance, R, and the voltage drop is measured by the electrometer voltmeter, V. Using this method, resistances up to about $10^{14}\Omega$ can be measured. Even though the basic procedure seems simple enough, some precautionary measures must be taken.

The input impedance of the voltmeter must be at least 100 times greater than the unknown resistance in order to avoid load-

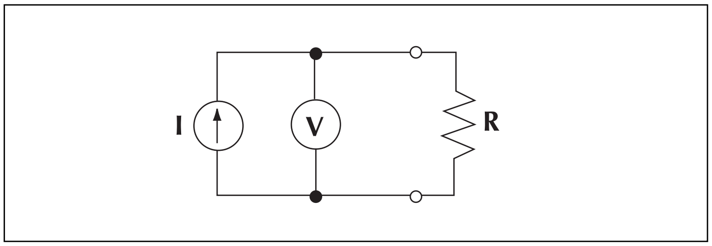

Figure 3: The constant current method for measuring resistivity

ing errors. Typically, the input impedance of the electrometer voltmeter is about $10^{14}\Omega$. Also, the output resistance of the current source must be much greater than the unknown resistance for the measurement to be linear. Since the voltage across the sample depends upon the sample resistance it is difficult to account for voltage coefficient when using the constant-current method.

The constant current method is used when determining high resistivity using the four-point probe or Van der Pauw technique. These methods of determining resistivity are often used on semiconductor material.

The Four-Point Probe Technique

The four-point collinear probe technique of resistivity measurement involves bringing four, equally spaced, electrical conducting pins in contact with the material of unknown resistance. The array is placed in the center of the material. A diagram of this technique is shown in ***Figure 4***.

A known current is passed through the two outside pins and the voltage is sensed at the two inside pins. The resistivity is then calculated from the following equation:

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

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

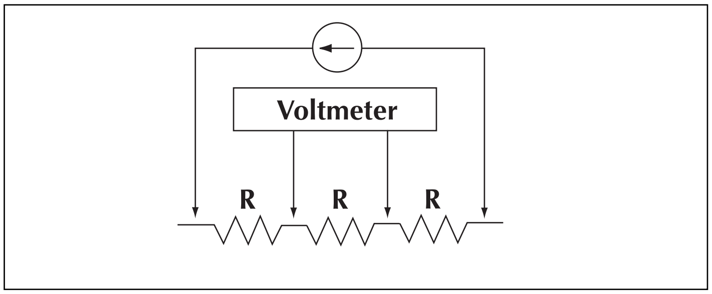

Figure 4: The four-point probe method for measuring resistivity

As shown in ***Figure 5***, a more realistic circuit would include a contact or spreading resistance at each probe (r), the finite resistance from LO to earth ground of both the current source (R_C) and the voltmeter (R_V), and the input resistance of the voltmeter (R_{IN}). Depending upon the material, the contact resistance, r, may be as much as 300 times or more than the measured resistance, R2. This requires that the current source have considerably higher compliance voltage than might be expected, and the voltmeter must have a much higher input resistance.

Since the current source is not completely isolated from earth ground, it becomes increasingly necessary to use a differential electrometer as the sample resistance increases. The problem exists because the sample, which has a very high resistance ($10^8\Omega$ or higher), will be of the same order of magnitude of the isolation (Input LO to chassis) of the electrometer voltmeter. For example, the isolation of the Model 6514 electrometer is $10^{10}\Omega$. As shown in ***Figure 5***, an AC current will flow from the LO terminal of the current source through the sample and finally from the Model 6514 LO terminal to ground. As shown in ***Figure 4***, this resulting voltage drop from pins r4 to r3 of the sample will cause erroneous results when the voltmeter measures the voltage drop between pins r2 and r3.

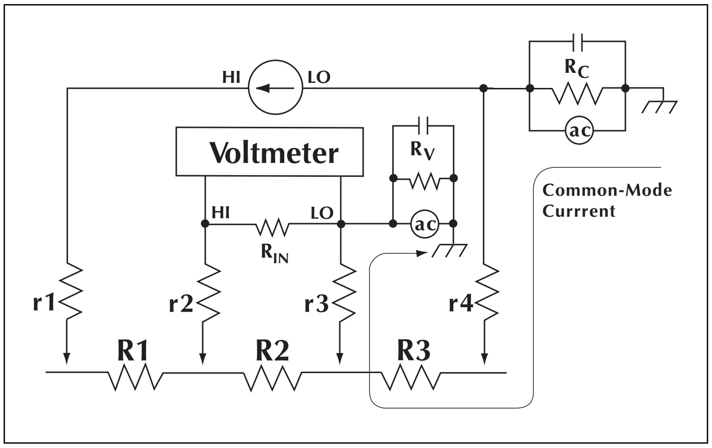

Figure 5: The realistic circuit of the four-point probe method

Using a differential electrometer eliminates this problem as shown in ***Figure 6***. The voltmeter will read the difference between the two buffer outputs which is equal to the voltage across R2. The values, r1, r2, r3, and r4, represent the resistance due to the probe in contact with the material. Since the unity-gain buffers have very high input impedance, little common-mode current will flow through r3 and the value of R2 can be calculated easily. The buffers can be any one of a range of JFET op amps, depending on how much offset current can be tolerated.

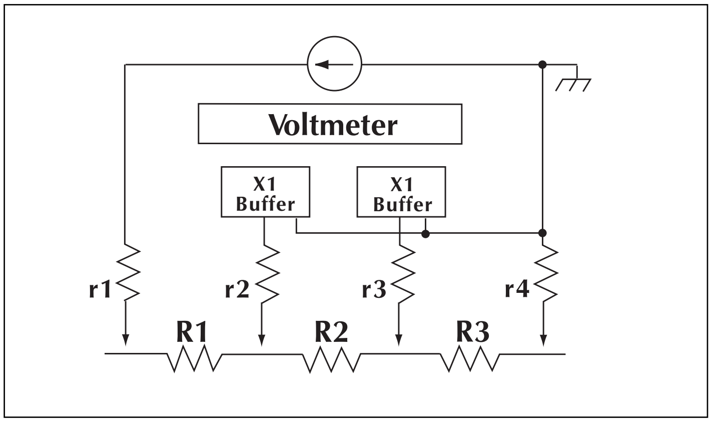

Figure 6: Making differential four-point probe measurements

To avoid leakage currents, either isolated or guarded probes should be used to make contact to the sample. The current source should be in the guarded mode. Guarding is discussed in the “Sources of Measurement Errors and Techniques to Reduce Them” section of the application note.

The Van der Pauw Technique

The Van der Pauw technique for measuring resistivity also utilizes a constant-current method. This technique makes use of four isolated contacts on the boundary of an arbitrarily-shaped lamilar sample. A total of eight measurements are made around the sample as shown in ***Figure 7***. These readings are combined mathematically to give the average resistivity of the sample. The formula for determining the resistivity is found in ASTM Method F76. This method is particularly useful with very small samples since the dimensions of the sample and the spacing of the contacts are unimportant.

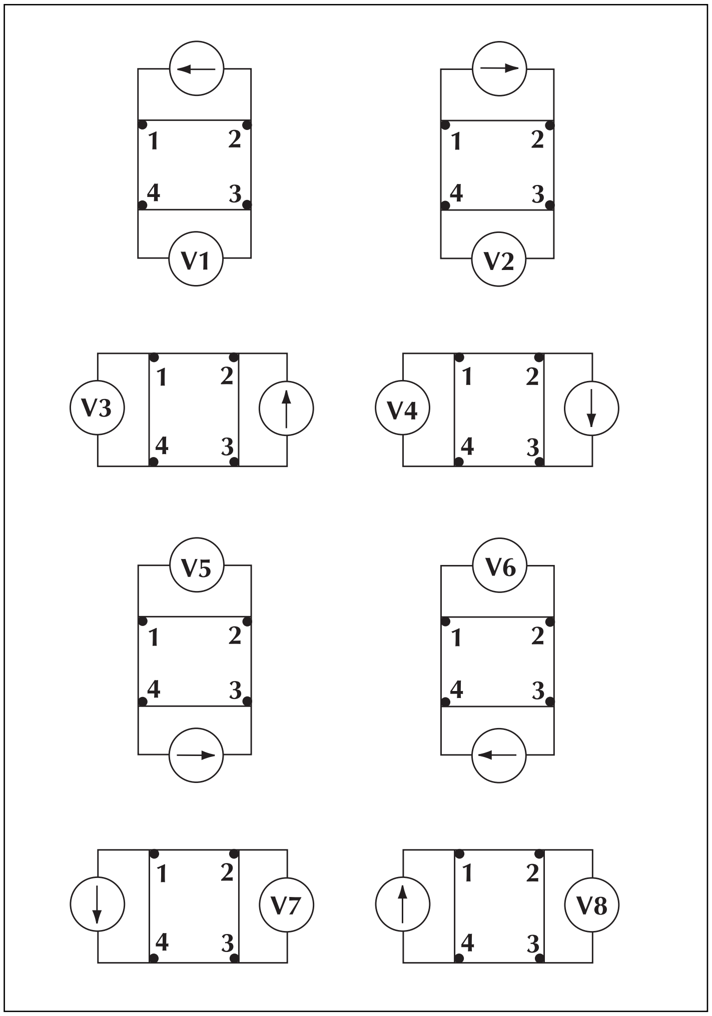

Figure 7: van der Pauw resistivity measurement conventions

As with the 4-point probe method, a differential measurement may be required if the sample resistance is of the same magnitude as the isolation of the voltmeter. As shown in ***Figure 8a***, common-mode current may flow between terminals 4 and 3 of the sample. ***Figure 8b*** illustrates how this problem can be resolved by using unity gain buffers and a differential measurement.

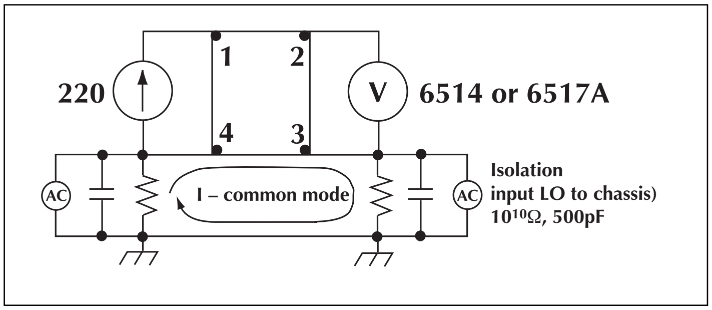

Figure 8a: Erroneous measurements caused by common-mode problems

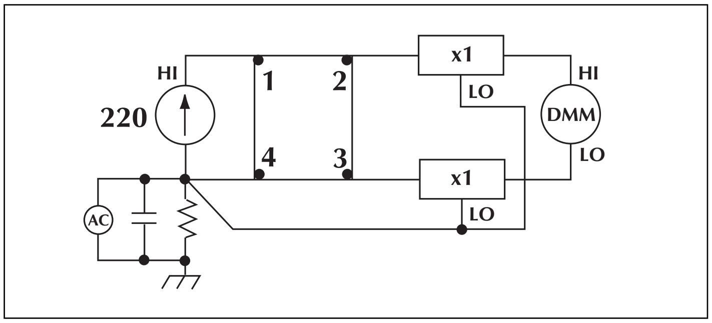

Figure 8b: Eliminating common-mode errors with a differential measurement

Another instrument setup designed to make differential Van der Pauw measurements is the Hall/Van der Pauw measurement system shown in ***Figure 9***. The system consists of the following Keithley instruments: Model 7065 Hall Effect Card, Model 2000 DMM, Model 220 Current Source, Model 486 Picoammeter, and Model 7001 Switch System. The current source and voltmeter are automatically switched to all sides of the sample using the 7065 Hall Effect Card. This eliminates the need to connect and disconnect the leads eight times. Also, the Model 7065 has built-in unity gain buffers so differential measurements can easily be made on high resistivity samples.

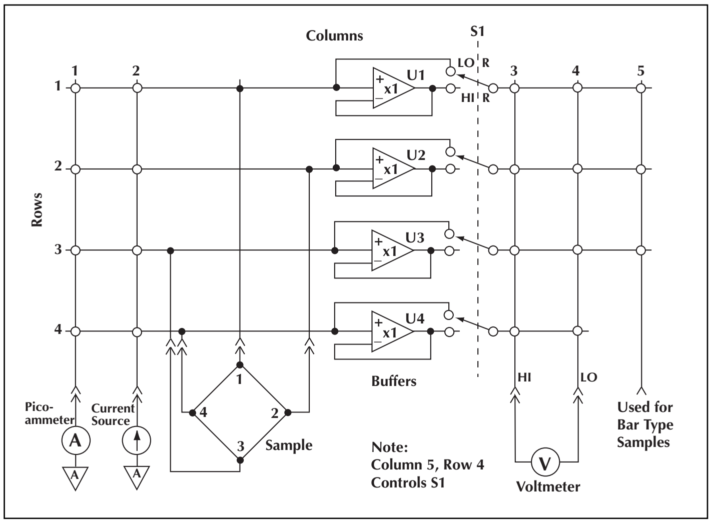

Figure 9

Sources of Measurement Errors and Techniques to Reduce Them

Electrostatic Interference and Shielding

Electrostatic interference occurs when an electrically charged object is brought near an uncharged object. Usually, the effects of the interference levels are not noticeable because the charge dissipates rapidly at low impedance levels. However, high resistance materials do not enable the charge to decay quickly and unstable measurements may result. The erroneous readings may be due to either DC or AC electrostatic fields. Electrostatic shielding will help minimize the effects of these fields.

DC fields can cause noisy readings or undetected errors. These fields can be detected when body movements near the experiments cause fluctuations on the display of the electrometer. A quick check for interference would be to place a piece of charged plastic, such as a comb, near the circuit. A large change in the measurement indicates the presence of static electricity.

Equally troublesome are AC fields which are most often caused by power lines and RF fields. If the AC voltage at the input is large, part of this signal is rectified causing an error in the DC signal being measured. This can be checked by observing the analog output of the electrometer with an oscilloscope. A clipped waveform on a more sensitive range indicates the need for better electrostatic shielding. To reduce the effects of the fields, a shield can be built to enclose the circuit being measured. An example of shielding is shown in ***Figure 10***. The shield is made from a conductive material and is always connected to the low impedance input of the electrometer or picoammeter. If circuit low is floating above ground, special safety precautions should be observed to prevent anyone from touching the shield.

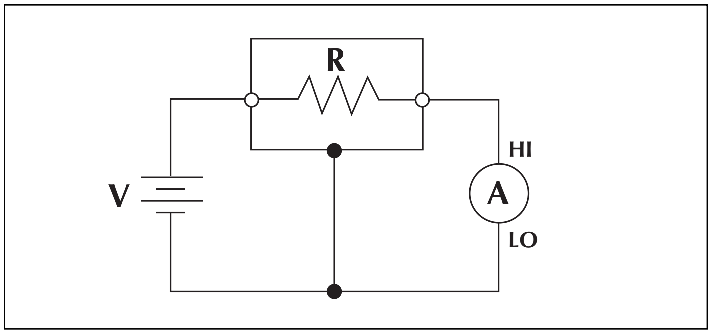

Figure 10: Shielding a high impedance device

A simple metal box or meshed screen that encloses the test circuit would be the easiest to make. Commercially available fixtures such as the Keithley Models 8002A High Resistance Test Fixture can provide shielding for small components. Keithley Model 8008 or 8009 Resistivity Test Fixtures can be used to test small (3-inch diameter) pieces of insulating materials.

The cabling in the circuit must also be shielded. Low noise shielded coax and triax cabling is available from Keithley. Low noise coax cable is Keithley part number SC-9, and low noise triax cable is part number SC-22.

Leakage Currents and Guarding

Leakage currents are generated by high resistance paths between low current conductors and nearby voltage sources. These shunt currents can considerably degrade the accuracy of high resistance measurements. Some ways to reduce leakage current are to use good quality insulators, reduce humidity, and use guarding. Guarding can also be used to reduce the effective capacitance of the measurement circuit.

One way to reduce leakage currents is to use good quality insulators when building the test circuit. The resistance of the test leads and test fixtures should be several orders of magnitude higher than the resistance being measured. Otherwise, the source resistance will be reduced by the inferior insulators. Some good quality insulators include Teflon, polyethylene, and sapphire. A further discussion on choosing the best insulator is found in Keithley's *Low Level Measurements*.

Humidity may also degrade high resistance measurements. The amount of water an insulator absorbs will vary depending upon the insulator. It is best to choose an insulator on which water vapor does not readily form on its surface. Sometimes this is unavoidable if the material being measured easily absorbs water, so it is best to make the measurements in an environmentally controlled room.

Another way to reduce leakage currents is to use guarding. A guard is a conductor connected to a low impedance point in the circuit that is nearly at the same potential as the high impedance lead being guarded. Guarding can isolate the high impedance input lead of an electrometer ammeter or picoammeter from leakage current due to voltage sources.

An example of guarding is shown in ***Figure 11***. In this example, the resistor being measured is supported on two insulators mounted in a metal test fixture. This circuit is guarded by connecting the LO of the picoammeter of the circuit to the metal case. This will put the top of the right insulator at almost the same potential as the bottom. The voltage difference is equal to the voltage burden of the picoammeter. Since the top and bottom

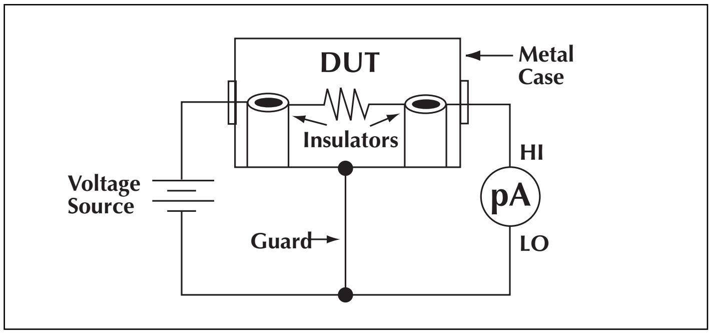

Figure 11: Guarding to reduce leakage currents

of the insulator are at nearly the same potential, no significant current will flow through it, and nearly all the current from the device under test will flow through the ammeter as desired.

Another example of guarding involves the leakage resistance of a coax cable. ***Figures 12a*** and ***12b*** show a high resistance source connected to a high impedance electrometer voltmeter. The leakage resistance, R_L, of the grounded shielded cable reduces the output voltage of the high resistance source. If instead of being grounded, the shield is connected to a low impedance source of the same potential as the high resistance source, the leakage between the two conductors in the cable will vanish because no voltage differential will exist. As shown in ***Figure 12c***, this low impedance source exists at the unity gain or preamp output of an electrometer. Current from the outer shield to ground may be considerable, but is of no consequence since it is supplied by a low impedance source rather than by the signal itself.

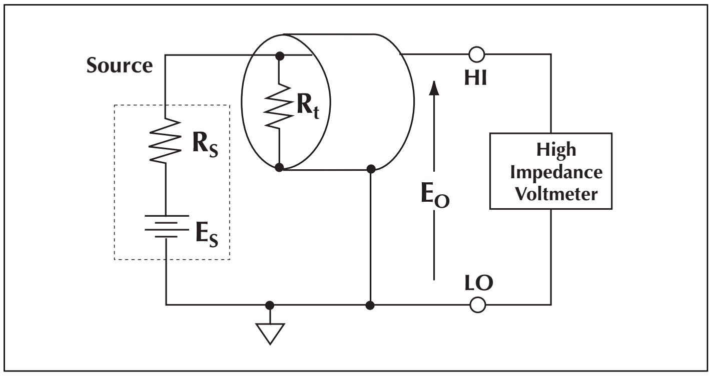

Figure 12a: A high resistance source is to be measured by a high impedance voltmeter

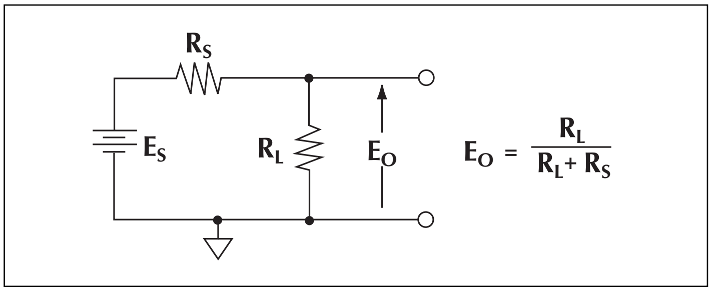

Figure 12b: Circuit showing loading effect of the connecting cable resistance R_L

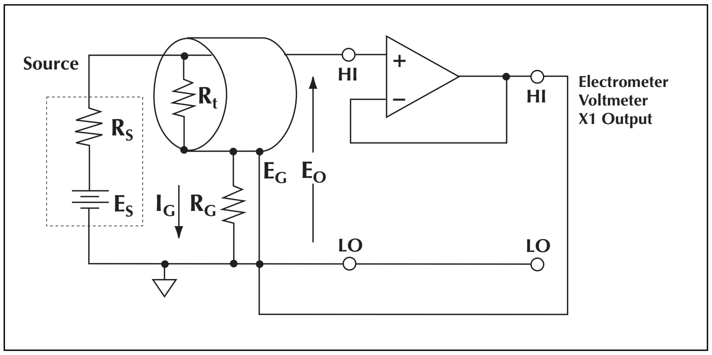

Figure 12c: A guarded configuration for the same measurement. No current flows through R_L since $E_O = E_O = E_G$

While reducing the effects of leakage current is the chief advantage of guarding, another is that it can reduce the effects of capacitance at the input of the electrometer voltmeter and ohmmeter. The rise time of the measurement is dependent upon both the source resistance and the effective capacitance, which consists of the electrometer input capacitance and the cable capacitance. Therefore, any capacitance in the test circuit can create a large RC time constant and thus slow measurement response times. For example, if the effective input capacitance of a test circuit is about 1000pF and the device under test is 200GΩ, then the RC time constant is 200s. If the measurement is to settle to within 1% of its final value (5 time constants or 1000s), settling will take about 16 minutes. This time factor is much too long, especially if the measurements are automated. By using the electrometer guard, the effective input capacitance can be reduced to about 20pF, thus reducing the time constant to four seconds. Most electrometers, like the Model 6430, 6517A, and 6514, have a built-in guard.

Triboelectric Effects

Triboelectric currents are created by the frictional motion between a conductor and an insulator. The motion causes free electrons to be removed from the metal, leaving a charge imbalance, which causes a current to flow. This effect occurs when insulators and conductors rub together such as in a coaxial cable.

The triboelectric effect can be reduced by using low noise cabling, which has a conductive lubricant such as graphite impregnated in the shield to reduce friction. If possible, the source of vibration should be removed.

Piezoelectric Effects

Piezoelectric currents are generated when certain insulators are mechanically stressed. Some materials that have this characteristic include crystalline materials, such as quartz, various ceramics, and some plastics.

The obvious way to reduce these currents is to reduce mechanical stress and use insulators that have a low piezoelectric effect, such as sapphire.

Alternating Polarity Method

When measuring materials with very high resistivity, background currents may cause measurement errors. Background currents may be due to charge stored in the material (dielectric absorption), static or triboelectric charge, or piezoelectric effects. Background currents can be equal to or greater than the current stimulated by the applied voltage. If the background current is the same polarity as the measured current, the resultant measured current value will be much higher than the true value. If the background current is the opposite polarity, these unwanted currents may cause a reverse polarity current reading. That is, the current polarity is opposite the polarity of the applied voltage, so the calculated resistance will be negative. To counter these problems, the Alternating Polarity Method can virtually eliminate the effects of background currents in the sample.

The Alternating Polarity Method applies a bias voltage of positive polarity, then the current is measured after a specified delay. Next, the polarity is reversed and the current is measured again, using the same delay. The polarity reversal process can be repeated any number of times. The resistance is calculated based on a weighted average of the most recent current measurements.

The Model 6517A Electrometer has the Alternating Polarity Method built into a test sequence. With this method, the user enters the test voltage, measurement time and the number of iterations. The final resistance value is calculated and stored in memory.

The Model 6524 High Resistance Software enables the user to view the actual current waveform that results from the applied alternating polarity test voltage. A typical waveform is shown in ***Figure 13***. Note the exponential decay in the current using both a positive and a negative test voltage. This pattern is repeated until stable and repeatable measurements occur. The marked Xs represent the calculated current based on a weighted average of the last few measurements.

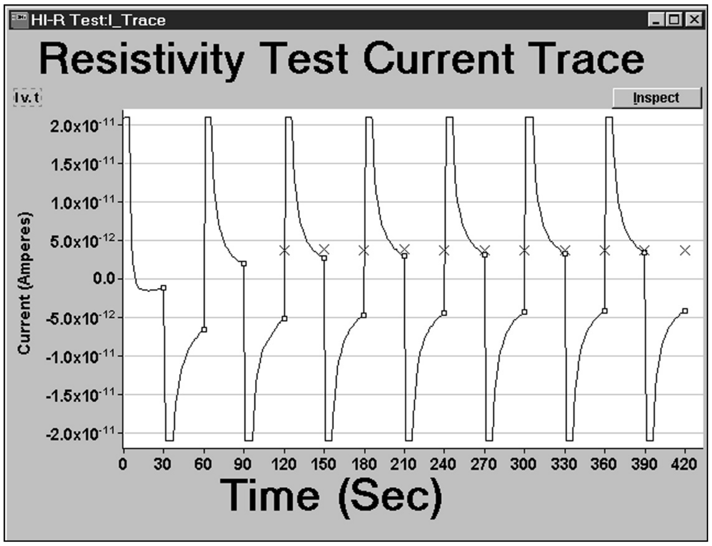

***Figure 13:** Actual current waveform resulting from applied alternating polarity voltage*

In addition to the Hi-R Test, the software includes three other programs. The HI-R Step Response Program analyzes the current transient from a single voltage step and can be used to determine the appropriate measure time for a given sample. The Hi-R Sweep Test will measure current or resistance while sweeping one of the following parameters: Alternating Voltage, Offset Voltage, or Measure Time. The Hi-R, T and RH program allows plotting resistance vs. time as well as either temperature or relative humidity, with appropriate probes.

Electrochemical Effects

Noise currents can also be generated by a contaminated insulator between two conductors of dissimilar metals. For example, epoxy printed circuit boards can generate up to a few nanoamps if not thoroughly cleaned of etching solution, flux and other materials. To avoid currents generated by this effect, eliminate dissimilar metals, clean insulators, and reduce humidity.

Source Capacitance

Problems may arise when measuring capacitive sourceswith a feedback ammeter such as the electrometer ammeter or picoammeter. Source capacitance makes the gain of the input stage of the ammeter increase with frequency. The small fluctuations from the source are now amplified and cause the measurements to be noisy.

There are two ways to overcome this problem. First, a battery can be used in place of the AC powered voltage source. This may not be practical if the system is to be automated. Another way to avoid noise amplification is to use a large resistor in series with the capacitive source. This will reduce the gain at high frequencies. Unfortunately, this will also increase the RC time constant and thus slow down the measurement response time.

Conclusion

Measuring high resistance is difficult but can be achieved using an electrometer and proper measurement techniques. Depending upon the application, either the constant voltage or the constant current method is used. Knowing the sources of measurement errors and taking the steps to eliminate them is essential to making meaningful high resistance measurements.

References

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ASTM, “1986 Annual Book of ASTM Standards,” Section 10, Volume 10.05 Electronics (II): Electrical Insulation and Electronics.

“Low Current Measurements,” Application Note 100, Keithley Instruments, Cleveland, Ohio, July, 2001.

Low Level Measurements, Keithley Instruments, Cleveland, Ohio, 1998.

Test System Safety

Many electrical test systems or instruments are capable of measuring or sourcing hazardous voltage and power levels. It is also possible, under single fault conditions (e.g., a programming error or an instrument failure), to output hazardous levels even when the system indicates no hazard is present.

These high voltage and power levels make it essential to protect operators from any of these hazards at all times. Protection methods include:

- Design test fixtures to prevent operator contact with any hazardous circuit.
- Make sure the device under test is fully enclosed to protect the operator from any flying debris.
- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.
- Use high-reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.
- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.
- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.

It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

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Printed in the U.S.A. **No. 1689** **11052KGW**