# Procedures and Pitfalls in Measuring Surface Resistance in Deposited Films at Very Low and Very High Values

When manufacturing resistive coatings that are not in the packaging range of 0.5 to 1.0 Ohms/square some different measuring techniques and precautions may be needed. The old tried and true procedure of applying a large current between two metallic idler rollers and measuring the voltage produced by the resistance of the web between the idlers may lead to some errors. In the case of 0.01 to 0.1 Ohms/Square (rfid and flexible circuitry applications) the necessary currents to get a voltage that is much larger than noise in the wiring system may require currents that can cause some damage to the coating at the contact lines. At the other end of the range, 50 to 5 million Ohms/square (microwave cooking and radar evading and spacecraft charge bleeding and electrostatic loudspeakers) plasmas being used in the coater or even inadvertently produced can "short out" the sample region and cause false readings. The high impedance resistor in the measuring circuit makes the circuit much more susceptible to noise. The average aluminizer boat currents provide a giant jumble of possible magnetically induced noise in the measurement circuits. Some rules of thumb will be presented and some interesting cases discussed. Much material has been extracted from the internet and citations as to where to find the original material are given.

Today there are many excellent resources with illustrations available on the internet. The author has reproduced several of them here along with the citation to find the original material. It seems wasteful to try to improve on other's good work. Examples from the author's experience are added in along with opinions as to suitable instrumentation.



## But first, what is "ohms per square"?

- It is important for predicting the rf absorption and rf reflection of sheets of material.
- If the conductive material is going to be patterned, then the Ohms/sq. value is used to compute the Resistance of traces in the resulting pattern.
- It is a nearly dimensionless measure of the resistance of a 2 dimensional surface. It depends on the resistivity of the material and the thickness.
    - We get to effectively ignore the material thickness
    - The thickness is "contained" in the value.
    - Resistivity has units of Ohm-cm (OK, Ohm-m if you are young)
    - Divide the coating resistivity in Ohm-cm by thickness in cm and you have it.
    - We measure the resistance of some size sample of the coating and then we have to convert it to Ohms/sq.
- It is not Ohms per square inch or Ohms per square unit of any unit of length.

## Concepts to keep in Mind

This example shows excellent figures for understanding basic Ohms/square relationships.

Figures and text by: Steve Fowler of
Fowler Associates for ESD Consulting and Testing ( http://www.sfowler.com).

## Ohms per Square What?

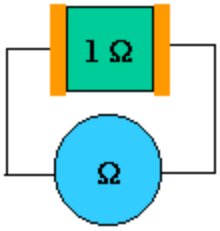
## The answer is: "It does not Matter." Square anything!

This term has been used for years by many who deal in electrical measurements but it is still not clearly understood. ASTM D-254 test method is used to measure the surface resistivity of materials. The units of measurement are Ohms per Square. Even though the ESD Associations Test Method S11.11 uses resistance

measured in Ohms, the resistivity of many materials is still required for characterization and contract requirements. Most people do not ask what it means for fear of showing their ignorance. Let's try to clear it up a bit.

Ohms per square is the unit of an electrical measurement of surface resistivity across any given square area of a material. It is the measurement of the opposition to the movement of electrons across an area of a material's surface and normalized to a unit square. This measurement is intended to be a basic material parameter and not dependent on absolute area, length or thickness. Unlike resistance, resistivity is not exactly a point-to-point measurement. It is a measurement where the electrons can take multiple paths across a uniform surface. However, the electrons are considered to generally flow only on the surface.

The measurement of resistance is not the same as resistivity. Resistance is the opposition to electron flow across or through a material, and is measured from point-to-point. It is not normalized. This measurement is very dependent on size, length, cross-section, etc.




Ohm Meter

Total R = 1 Ω



The above figure shows the measurement of a material with the same dimensions on all sides. It is a square area of the material. It can be 1 inch or 1 mile on a side. When electrodes are attached as shown, and the Ohm meter measures 1 Ohm, we can state that this material has a surface resistivity of 1 Ohm per square.

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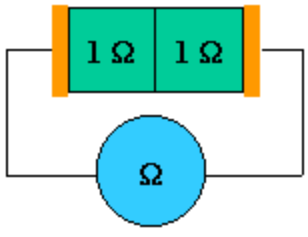
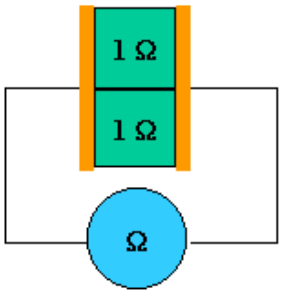
If two squares of the material (the same size as above) are laid end to end and electrodes attached as shown below, the resistance is the addition of these two squares or 2 Ohms. This measurement is of two resisters in series.




Ohm Meter

Total R = 1 + 1 = 2 Ω

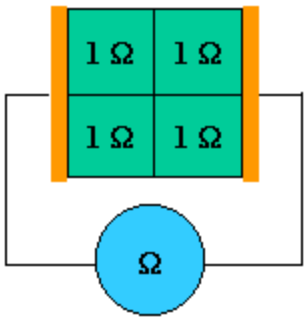
Or if two of these squares are stacked as shown below, the resistance is that of two resistors in parallel or 1/2 Ohm.




Ohm Meter

$$\text{Total R} = \frac{1 \times 1}{1+1} = 1/2\ \Omega$$

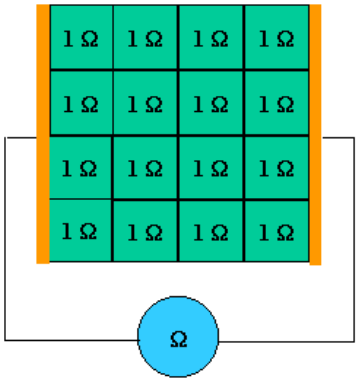
Now if we combine these two examples we have four squares of the materials in an arrangement of two parallel resisters in series. Or the resulting four resisters which now form a square again read 1 Ohm on the Ohm meter.




Ohm Meter

$$\text{Total R} = \frac{1 \times 1}{1+1} + \frac{1 \times 1}{1+1} = 1\ \Omega$$

If we take the examples to a higher level where we have 16 squares of the material arranged as shown below, the result is again 1 Ohm. It is again in this example a square. If the first example is 1 square inch then this example is 4 square inches and the results are the same - 1 Ohm.




Ohm Meter

$$\text{Total R} = \frac{1 \times 1 \times 1 \times 1}{1+1+1+1} + \frac{1 \times 1 \times 1 \times 1}{1+1+1+1} + \frac{1 \times 1 \times 1 \times 1}{1+1+1+1} + \frac{1 \times 1 \times 1 \times 1}{1+1+1+1} = 1\ \Omega$$

So you see that it really doesn't matter. A square inch or a square mile of a material with a surface resistivity of 1 Ohm per square will read just 1 Ohm on an Ohm meter.

## Why don't we get handbook values for conductivity (resistivity)?

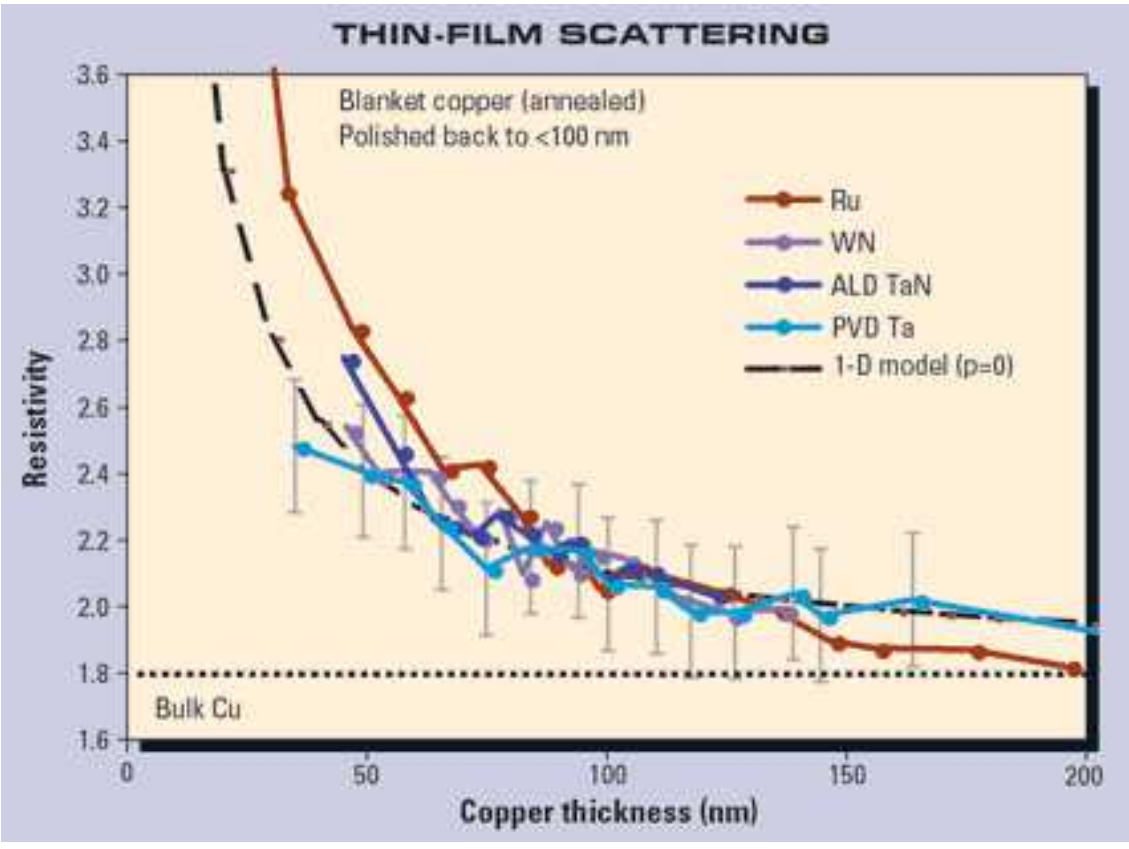
There are complications due to thin films, grain size and quantum mechanics:

Fundamental limits often constrain the function of materials and processes as dimensions are decreased. In the case of interconnects, the first physical limit that is reached is the mean free path of electrons in the metal interconnect. When dimensions of a metallic line are less than or equal to the mean free path, then scattering from the surfaces of the line start to add to the intrinsic scattering from phonons, and the scattering time of the electrons is reduced. For copper interconnects, the mean free path of electrons is ~40 nm at room temperature, and the dimensions of lines at the first few metal layers are now <70 nm. Thus, the resistivity of copper will increase from the additional scattering from interfaces. Scattering from grain boundaries also plays an increased role as the dimensions of the line start to restrict grain growth. This increase in resistivity at small dimensions is known as the finite size effect for copper lines.

**The effects of Quantum mechanics of surface scattering for various Cu films on various barrier layers in semiconductors**.

From: Semiconductor International, 5/1/2006






I have always found that a value of 200 Ohm-Angstroms or 2.0 mOhm-cm to be a useful number. For Al films, a value of 300 Ohm-Angstroms or 3.0 mOhm-cm will let you estimate most jobs.

## 2 Wire vs. 4 Wire

The following section is extracted from:

## The Art of Measuring Low Resistance

by Tee Sheffer and Paul Lantz, Signametrics

found at:

http://www.evaluationengineering.com/archive/articles/1106/1106the_art.asp

## Don’t heap all the blame for a wrong measurement on the DMM (Digital Multi-Meter). There can be several less obvious sources of the errors.

Testing assemblies and components usually includes checking the continuity of connectors, wires, traces, and low-value resistive elements. Such applications typically require both a DMM and a switching system.

Many users select a DMM and switching cards based only on the specifications of the DMM and later are surprised to find that their measurements are an order of magnitude less accurate than expected. Many users don’t recognize the error as a system problem and conclude that the DMM is not meeting its specification.



Making accurate, stable, and repeatable resistance measurements is an art. There is plenty of technology involved, but the art is an important part, especially when you are measuring low resistance values.

To achieve your accuracy goal, you need to understand the error sources in your application. It is important to start with a good DMM. But there are significant error sources outside the DMM, some of which may not be obvious. Things may be more complex than they seem, and some types of errors may be misinterpreted.

## Limitations and Error Sources

Not all materials are created equal. Most connectors and test probes are made of beryllium-copper or phosphor-bronze materials that closely match the electromotive force (EMF) of copper. For this reason, they do not cause significant thermally induced voltage errors.

However, relays and some other devices use nickel-iron alloys that do not match the properties of copper. These can cause significant thermal EMF errors. Thermal voltages are generated when there is a mismatch of materials combined with a temperature difference.

This is the same principle that makes thermocouples work as temperature sensors. If you expect readings that are accurate within a few milliohms, this is a big issue. This error source also affects higher value resistance measurements but to a lesser degree.

It is easy to overlook second-order specifications of a DMM, such as current drive levels used for resistance measurement. These specs may be in small print or missing, but they are important. For measuring low resistance, this spec tells what you can expect from the DMM. The accuracy specs of the DMM don’t tell the whole story. For example, the Signametrics SMX2064 PXI DMM uses a 10-mA current source while most other DMMs are limited to 1 mA or less. Remember Ohm’s Law: $V = I \times R$ means that 10 times the current produces 10 times the voltage being sensed across the resistor. This larger signal is less susceptible to external errors and noise and provides more signal to measure.

The larger signal almost always produces a more accurate measurement. It is confusing to compare two DMMs having similar specifications in ohms if one has 10 times the current drive. The two are not the same. The one with the higher current will perform better, especially in a system.

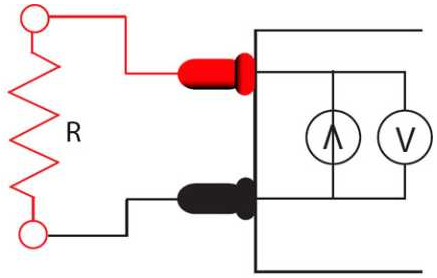
Good DMMs can measure signals down to a few microvolts. If you need to measure a resistance down to a few milliohms, a 1-mA test current only produces 1 µV of signal per 1 mOhm of resistance. In other words, you are operating right at the resolution limit of the DMM.

With a 10-mA test current, there are 10 µV of signal per 1 mOhm of resistance. As a result, a DMM that uses 10× as much current for this test will give about 10× improvement in accuracy, stability, and repeatability for very low values.

If your test has serious throughput requirements and you need to make hundreds of measurements per second, having a stronger signal combined with good noise performance in the DMM makes a huge difference. Remember that the DMM's accuracy at higher speeds may be much more important than its best accuracy.

## Two-Wire Ohms

Everyone knows how easy it is to measure resistance using a two-wire connection. However, for low resistance, a two-wire connection has disadvantages.



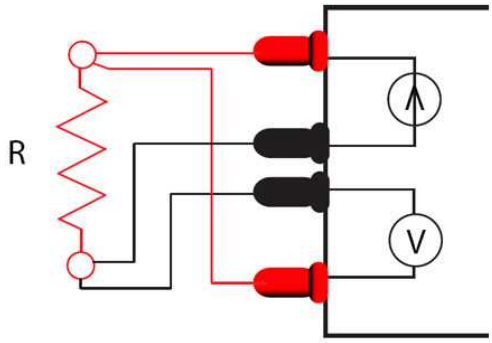

Two-Wire Ohms?

Test leads frequently add >1 Ohms of resistance, and your test probe may add another 0.1 Ohms of contact resistance to the measurement. These errors are significant if you are measuring 20 Ohms.

You can eliminate most of the test-lead errors from a two-wire connection by shorting the leads and setting the Relative-Ohms control. This enables the DMM to subtract the test-lead resistance from the readings that follow. This is a very handy tool when you are doing manual testing, but it is less useful in an automated test.

### Four-Wire Ohms

A four-wire connection is the standard method for measuring low resistance. It eliminates the resistance of the test leads from the measurement. One pair of leads carries the test current while the other pair of leads senses the voltage across the resistor under test.




Four-Wire Ohms

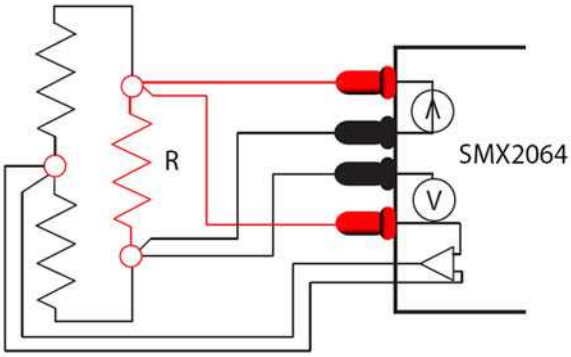
The resistance of the current-carrying leads doesn't matter because they are not in the measurement path. The resistance of the sensing leads doesn't matter since they don't carry any current.

A four-wire connection is not immune to thermal EMF errors caused by mismatched materials. This usually is not important in manual testing situations, but it is a major issue in automated systems where a relay switch is used.

**Six-Wire Ohms (if you really are measuring patterns on a surface)**

What if the resistor you want to measure is in a circuit with other components or resistors as in networks or on a loaded circuit board? Then you need a six-wire guarded connection. This method makes it possible to measure resistance in situations where it would be impossible otherwise. The SMX2064 DMM offers this capability.






Six-Wire Guarded Ohms In-Circuit Measurement

A guard amplifier drives the junction of parallel components to a voltage level that prevents any of the test current from leaking away from the resistor under test. This is a standard method used by large ATE in-circuit test systems. With the right DMM, you can implement it too.

### Measuring Through a Switch Matrix

Many applications are for production test. In these cases, it is almost always necessary to perform multiple tests and measure multiple points. You usually do this by putting a switching card or a matrix ahead of the DMM. It is important to note that the switching card can be a major source of error, particularly when measuring low resistance.

### Two-Wire With a Switching Card

How does adding a switching card affect your two-wire resistance measurements?

Two-wire resistance measurements certainly are attractive because you can fit twice as many two-wire measurements onto a card as you can four-wire measurements

.
The economics are attractive. Perhaps you can put a short circuit on one of the inputs to the switching card and measure that short to make a Relative-Ohms measurement? This line of reasoning also might lead you to select the highest density switching card possible.

However, there are reasons to be careful. A typical switching card does not have the same resistance through all of its channels. Channel 0 may add 0.2 Ohms to the reading while Channel 20 may add 0.8 Ohms. Consequently, measuring a short on one does not give a good compensation for the other because they do not have the same resistance.

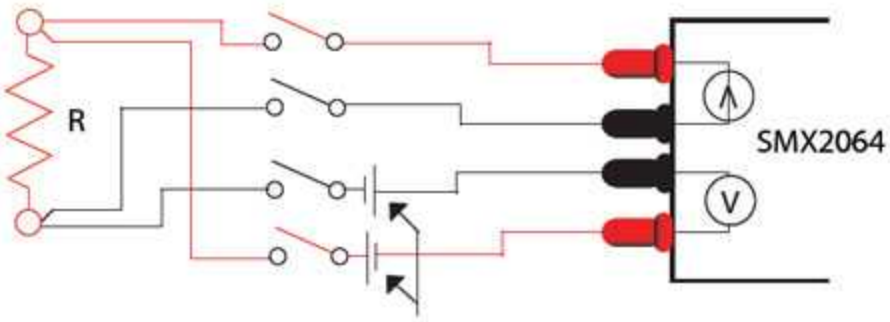
Even if you could correct for the difference in channel-to-channel resistance, relays typically have about 50 mOhms of contact resistance that will shift around by 20 mOhms from one reading to the next. You might think that high-current relays will have lower contact resistance, but it doesn't work that way. High-current relays usually have silver-plated contacts that give low resistance for currents above 100 mA. Unfortunately, silver-plated contacts have a high and unpredictable contact resistance for currents less than 50 mA.

Relays are made of nickel-iron materials, and they all have problems with thermal EMFs. Frequently, this error source is not specified for high-density switching cards. If not, the thermal voltages probably are around 100 µV. If your DMM uses 10 mA to make this measurement, the switching card adds 10 mOhms of error to the measurement. If your DMM uses only 1 mA, the switch will add 100 mOhms of error to the measurement.

Keep in mind that this error voltage is made up of all of the closed relay contacts connected to the sense lines of the DMM. The more complex the switching system is, the higher the error will be.

**Four-Wire With a Switching Card**

Using a four-wire connection through your switching card takes care of the resistance issues associated with the switching card. This accuracy improvement happens at the expense of reduced channel density. However, it does not take care of the thermal EMF problems that come with some switching cards .




Thermal Voltage Errors, Not Corrected

Four-Wire Ohms Switching Card

One way to reduce this error is to use a DMM with the Offset-Ohms function. However, this method is very slow, it adds noise, and it is limited in its capability to reduce the error. For best results, start with a high-quality switching card that is specified for low thermal EMF error.

If you need to measure low resistance values, you benefit by using a DMM that has a 10-mA excitation current. A 1-mA source gives a much weaker signal to measure and presents system-level problems,

particularly if there are switching cards involved. If you expect a stable, accurate result, you almost certainly need to use a four-wire connection.

The accuracy spec of the DMM is important but not the whole story. Remember that everything in the measurement path affects the accuracy of the measurement, especially switching cards. Your best bet is to combine a DMM with good ohms specifications and high test current and a switching card with a low thermal EMF spec, preferably an instrumentation type.

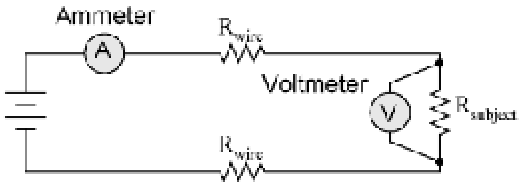
When passing a current through the sample, some of the current may pass through the surface and some through the bulk (depending on the relative resistances of the surface and bulk). The surface resistance depends only on the surface resistivity whereas the bulk resistance depends on the product of the bulk resistivity and the probe spacing (s). Therefore, probes with a smaller spacing are more surface sensitive.

## Kelvin (4-wire) resistance measurement explained from a slightly different point of view.

Suppose we wished to measure the resistance of some component located a significant distance away from our ohmmeter. Such a scenario would be problematic, because an ohmmeter measures *all* resistance in the circuit loop, which includes the resistance of the wires (Rwire) connecting the ohmmeter to the component being measured (Rsubject):


Ohmmeter indicates $R_{wire} + R_{subject} + R_{wire}$

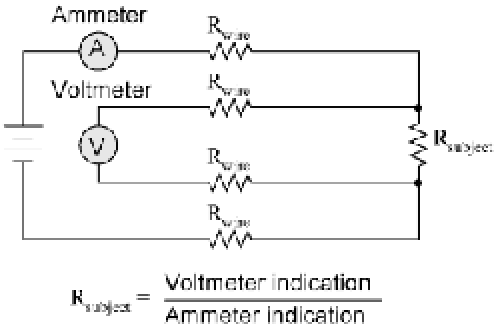
Usually, wire resistance is very small (only a few ohms per hundreds of feet, depending primarily on the gauge (size) of the wire), but if the connecting wires are very long, and/or the component to be measured has a very low resistance anyway, the measurement error introduced by wire resistance will be substantial. An ingenious method of measuring the subject resistance in a situation like this involves the use of both an ammeter and a voltmeter. We know from Ohm's Law that resistance is equal to voltage divided by current (R = E/I). Thus, we should be able to determine the resistance of the subject component if we measure the current going through it and the voltage dropped across it:



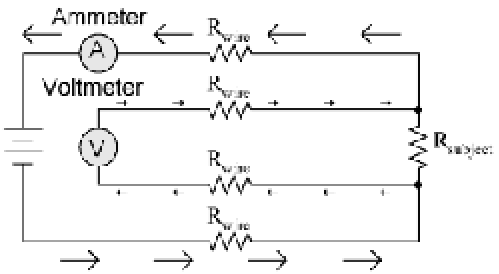

$$R_{subject} = \frac{\text{Voltmeter indication}}{\text{Ammeter indication}}$$

Current is the same at all points in the circuit, because it is a series loop. Because we're only measuring voltage dropped across the subject resistance (and not the wires' resistances), though, the calculated resistance is indicative of the subject component's resistance (Rsubject) alone.

Our goal, though, was to measure this subject resistance *from a distance*, so our voltmeter must be located somewhere near the ammeter, connected across the subject resistance by another pair of wires containing resistance:



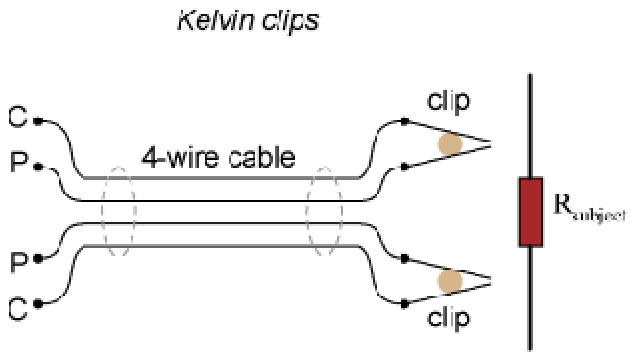

At first it appears that we have lost any advantage of measuring resistance this way, because the voltmeter now has to measure voltage through a long pair of (resistive) wires, introducing stray resistance back into the measuring circuit again. However, upon closer inspection it is seen that nothing is lost at all, because the voltmeter's wires carry miniscule current. Thus, those long lengths of wire connecting the voltmeter across the subject resistance will drop insignificant amounts of voltage, resulting in a voltmeter indication that is very nearly the same as if it were connected directly across the subject resistance:




Any voltage dropped across the main current-carrying wires will not be measured by the voltmeter, and so do not factor into the resistance calculation at all. Measurement accuracy may be improved even further if the voltmeter's current is kept to a minimum, either by using a high-quality (low full-scale current) movement and/or a potentiometric (null-balance) system. Kelvin resistance measurement 4-wire resistance measurement

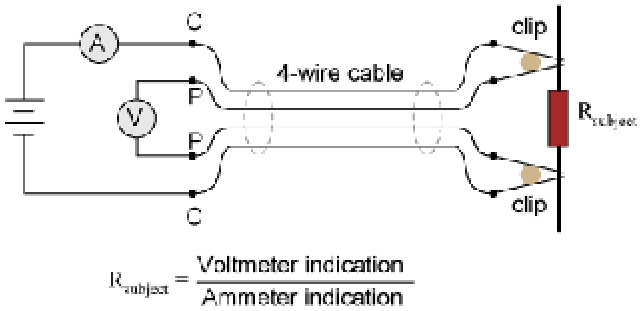
**Four-wire resistance measurement**

This method of measurement which avoids errors caused by wire resistance is called the *Kelvin*, or *4-wire* method. Special connecting clips called *Kelvin clips* are made to facilitate this kind of connection across a subject resistance: Kelvin clips




Alligator clips, Kelvin clips

In regular, "alligator" style clips, both halves of the jaw are electrically common to each other, usually joined at the hinge point. In Kelvin clips, the jaw halves are insulated from each other at the hinge point, only contacting at the tips where they clasp the wire or terminal of the subject being measured. Thus, current through the "C" ("current") jaw halves does not go through the "P" ("potential," or *voltage*) jaw halves, and will not create any error-inducing voltage drop along their length




$$R_{subject} = \frac{\text{Voltmeter indication}}{\text{Ammeter indication}}$$



### Cabling Concerns

Some excellent comments on how to arrange leads from:

Cirris Systems (http://www.easy-wire.com/testing/index.html) –
Technical Tips (http://www.easy-wire.com/testing/twisted_pair/index.html) –
Twisted Pair Testing



## What are twisted pairs?

- Two wires twisted together form a *twisted pair.*
- Usually, there are several twisted-pairs in a twisted pair cable.
- In higher performance cables each twisted pair will be shielded.

## Why do they put twisted pairs in cables?

**It is an extremely effective way to send high-speed signals down a cable because:**

- Most electrical noise entering into and/or radiating from the cable can be eliminated.
- Cross-talk (signals leaking between wires in a cable) is minimized.

## Why do signals leak between wires?

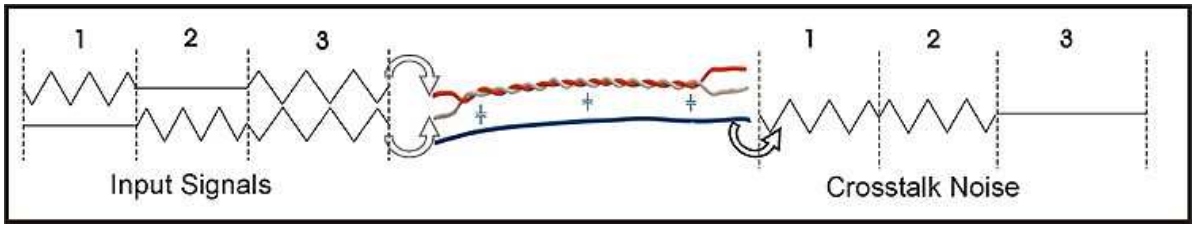
In addition to energy flowing down a wire, it can flow between wires due to the electrostatic and magnetic effects that occur when voltages or currents in the wire change. In understanding electrostatic effects, consider that "insulation between two conductors" is the definition of a capacitor. More surface area (longer cables) means more inter-wire capacitance. Adjacent wires in the same cable behave as though capacitors are connecting them together, thus higher frequency signals can leak, or "cross talk", from wire to wire through this capacitance.

## How does twisted pair cabling minimize the effects of capacitance?

## A. Cross-talk (leaking signals)

Signals are sent down twisted-pair wires such that when one wire in the pair becomes positive the other wire becomes negative by the same amount. Any other wires close to this pair will be affected by cross-talk equal to the sum of the two signals, so if this sum is zero (or nearly zero) then the affects of cross-talk are eliminated.

Notice in period 1 in the illustration below the signal sent through the orange wire shows up on the black wire. In period 2 the signal sent through the white wire shows up on the black wire. In period 3 the signal sent through the orange wire and it's opposite polarity signal on the white wire cancel each other out, leaving no effect on the black wire

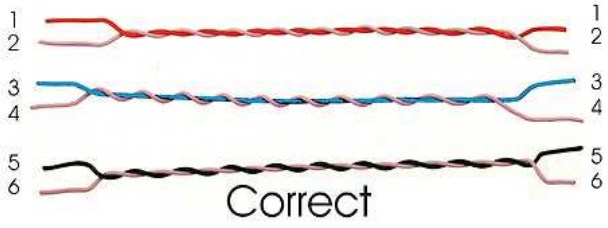


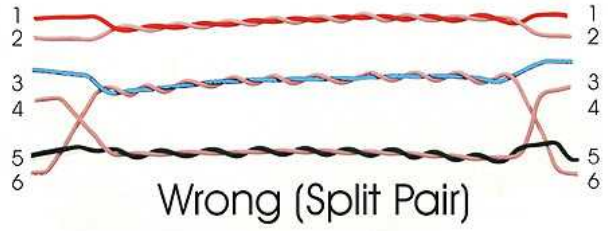

**B. Immunity to Electrical Noise** The receiving electronics is intended to detect only the difference in polarity between the two wires in the twisted pair. Since electrical noise affects both wires of a twisted pair equally the receiving electronics gets a true signal by rejecting signals on the twisted pair that move toward the same polarity.

**Question:** If I am using a good, certified, twisted pair cable and I test for opens, shorts and even perform high voltage insulation tests, is this enough to assure the quality of my assemblies?

**Answer:**

Continuity, resistance, and insulation tests can tell you if the connections are correct but they can NOT tell you anything about the noise canceling effects provided by twisted pairing. A common and serious error in a twisted pair cable is a "*split pair*".



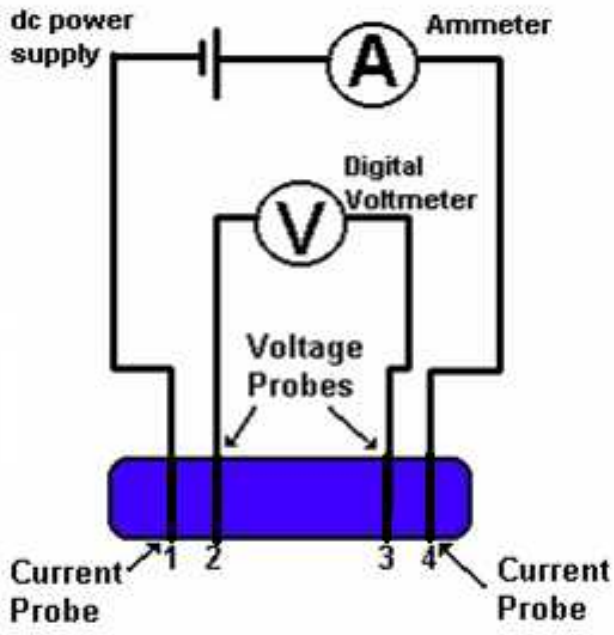




This error occurs when one wire from each of two different pairs gets swapped on both ends of the cable. In our example above, you can see that the white wire of the blue & white twisted pair (pin 4) and the white wire of the black & white twisted pair (pin 6) have been swapped on both ends. The result is a cable that will pass a standard continuity test, but will have serious cross-talk problems. Split pair errors can easily happen in twisted pair cables where one wire of each pair is the same color. Some twisted pair cables have wires of all the same color, making this type of error even easier to produce and harder to find. Even when all the colors are different, it is not that hard to make a mis-wire on one end that is caught during a continuity test and then "fix it" at the other end so that the continuity test passes but a split pair error now exists.



## What Should Our Sample Look Like?

- **Often is it a 1 inch by full web width sample.**
- **Very often it is a 1 inch by 6 inch piece cut from the web.**



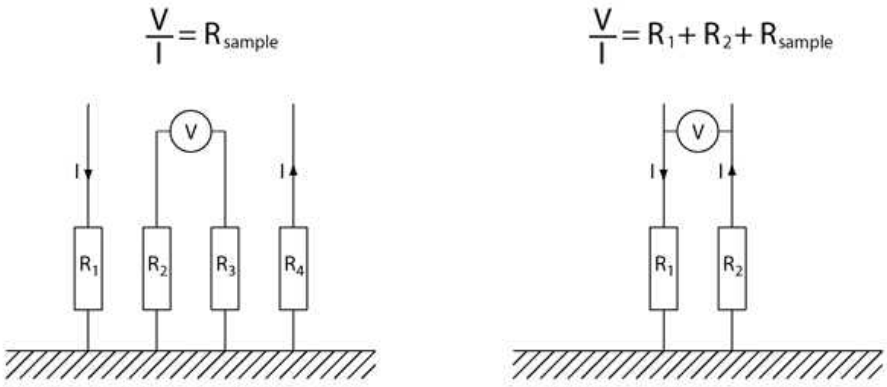

We count the “squares” between line probes 2 and 3. The count is simply the length between 2 and 3 divided by the width. The R/sq. is the measured R divided by the count. It is that simple. If the probe assembly is walked across a longer sample a good measure of the profile of the resistance is obtained. If the length between 2 and 3 is about one square a series of measurements across the web gives a good profile.

Watch out for scratches in the web. This test will virtually ignore scratches in the long direction. Scratches across the sample are fatal. It is a good way to check if the incoming material possibly has deep scratches before metallizing. In that case the values found when measuring across the web will be higher than the ones if the samples are cut down web.

## Why use 4 point probes?

The simplest way to measure conductivity is with a multimeter, however, this doesn't give the right answer: Consider a simple multimeter that is set to measure resistance. The meter is then connected across the sample in the standard way using the two probes supplied. The resistance that you measure is actually the sum of the resistances of the sample, the probes, the cables and so on. To demonstrate this, one could connect the two probes together and the meter would still measure some resistance. For most applications, this isn't a significant problem since the resistance of the wires and probes is a lot smaller than the resistance of the sample. However, if one were to use very small probes this problem would become significant. Furthermore, if the sample is semiconducting, then the contact between the probe and the sample may act as a Shottky diode, and thus have a high (and non-ohmic) resistance.

These problems can be simply overcome by using 4 co-linear probes. If a known current is passed through the sample using two of the probes and if the potential difference between the other two probes is measured without drawing any current (i.e. with a high impedance voltmeter), then the resistance of the sample can be measured independently of the contact resistances. This is illustrated in the following figure:




*By using 4 probes, the sample resistance can be found independently of the contact resistances.*

The purpose of the 4-point probe is to measure the resistivity of any semiconductor material. It can measure either bulk or thin film specimen, each of which consists of a different expression. The derivation will be shown in this tutorial.

The 4-point probe setup used consists of four equally spaced tungsten metal tips with finite radius. Each tip is supported by springs on the other end to minimize sample damage during probing. The four metal tips are part of an auto-mechanical stage which travels up and down during measurements. A high impedance current source is used to supply current through the outer two probes; a voltmeter measures the voltage across the inner two probes to determine the sample resistivity.



**Theory**

For a thick Sample

In our derivations for this section, we assume that the metal tip is infinitesimal and samples are semi-infinite in lateral dimension. For bulk samples where the sample thickness t >>s, the probe spacing, we assume a spherical protrusion of current emanating from the outer probe tips. The differential resistance is:

$$\Delta R = \rho\left(\frac{dx}{A}\right)$$

We carry out the integration between the inner probe tips (where the voltage is measured):

$$R = \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x^2} = \frac{\rho}{2\pi}\left(-\frac{1}{x}\right)\Big|_{x_1}^{x_2} = \frac{1}{2s}\frac{\rho}{2\pi}$$

where probe spacing is uniformly s. Due to the superposition of current at the outer two tips, R = V/2I. Thus, we arrive at the expression for bulk resistivity:

$$\rho = 2\pi s\left(\frac{V}{I}\right)$$

**Thin Sheet**

For a very thin layer (thickness t << s), we get current rings instead of spheres. Therefore, the expression for the area $A = 2\pi xt$ . The derivation is as follows:

$$R = \int_{x_1}^{x_2} \rho \frac{dx}{2\pi xt} = \int_{s}^{2s} \frac{\rho}{2\pi t}\frac{dx}{x} = \frac{\rho}{2\pi t}\ln(x)\Big|_{s}^{2s} = \frac{\rho}{2\pi t}\ln 2$$

Consequently, for R = V/2I, the sheet resistivity for a thin sheet is:

$$\rho = \frac{\pi t}{\ln 2}\left(\frac{V}{I}\right)$$

Note that this expression is independent of the probe spacing s. In general, the sheet resistivity

$$R_S = \rho/t$$

can be expressed as:

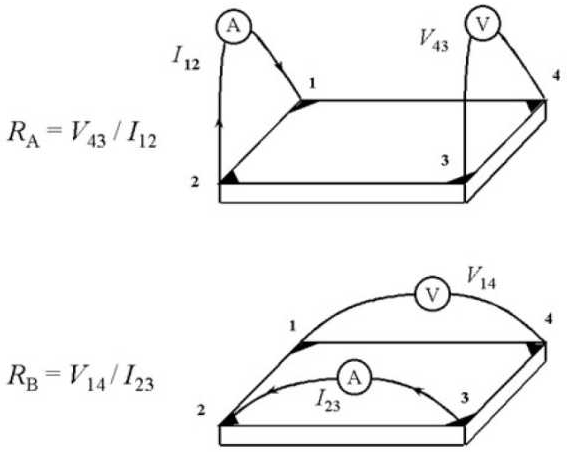
$$R_S = k\left(\frac{V}{I}\right)$$

where the factor k is a geometric factor. In the case of a semi-infinite thin sheet, k = 4.53, which is just $\pi/\ln 2$ from the derivation. The factor k will be different for non-ideal samples.

They are useful with ITO films. Use the largest radii tips available.

## The Ultimate 4 Point Test, Van Der Pauw's Theorem

- The 4 probes do not have to be in a straight line. It is just the simplest case to compute.
- The test sample can be any simple closed shape, round, square, oblong, but no donut holes.
- The test configuration used in semiconductor work is very sensitive.
- It can be very useful in patterned conductor work.
    - The test patterns can be tucked into non-used areas and available for immediate test on the roll.



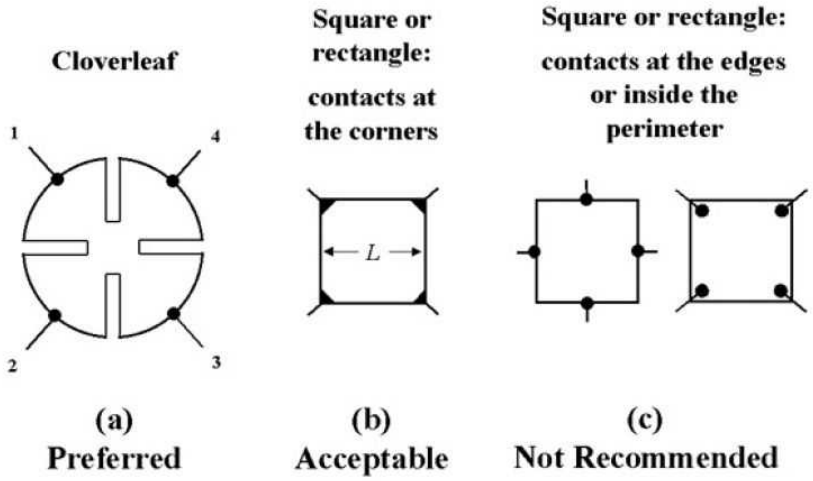

Schematic of a Van der Pauw configuration used in the determination of the two characteristic resistances RA and RB.

Just take the $R_A$ and $R_B$ results and plug into this equation and solve it for $R_S$. Give thanks for computers, this used to be hard.

$$\exp(-\pi R_A/R_S) + \exp(-\pi R_B/R_S) = 1$$



## Van der Pauw Geometries



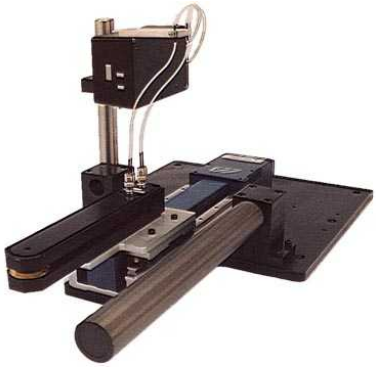

Sample geometries for Van der Pauw resistivity and Hall effect measurements. The cloverleaf design will have the lowest error due to its smaller effective contact size, but it is more difficult to fabricate than a square or rectangle.

## Non Contact methods.

- When to use them.
  - When probing may cause visible damage or a possible defect in an electronic circuit.
  - If you are making non uniform resistance across the web and you need in-coater measurements.
- Pitfalls.
  - They need frequent calibration.
  - You will need calibration sheets to slip between the sensors.
    - This can be an access problem in a coater.
  - They are excellent temperature sensors.
  - Don't let them vibrate.
- The author is familiar with about four types of systems, two from Europe and two from America.
  - The most robust has been one from America, Delcom.
  - Lehighton makes several benchtop models.

Note the water cooling lines, very necessary, if in a coater.

A scanning type.



There is also a hand held capacitance type gauge (order of magnitude) that is useful for electrostatic discharge protection films

## Problems at Very Large Values of Surface Resistance, $10^3$ to $10^8$ Ohms/sq.

- Who needs it?
  - Bleeding surface charge from spacecraft in high orbit.
  - Making electrostatic loudspeakers.
  - Lining accelerator tunnels for physics research.
- Who is your enemy?
  - Long connection leads.
  - Every radio station in the area.
  - If you evaporate, every high current transformer's stray magnetic fields.
  - If you sputter, possible plasma leaks bridging exposed connection points.

- What do you do?
    - Always use twisted pairs of leads if possible
    - Use shielded cable if possible.
    - Don't let cables vibrate. Stray capacitance may induce microphonic signals.
- Above ~$10^5$ Ohms/sq. you will need special test fixtures for repeatable results.

Twisted lead pairs and preferably shielded lead pairs are very necessary. Measuring these resistance values in a coater is very difficult. Measuring them in the testing laboratory is problematic. Just moving your hands in the vicinity of test leads will probably cause reading fluctuations. If you need more than 1 digit accuracy, be prepared to spend a few thousand dollars. If you only need order of magnitude accuracy, economical instruments are available.

## Summary

- There are lots of ways to get misleading results.
- Study the literature.
- Some of the instrument manufacturers publish excellent applications manuals.
- If you use 4-pt. linear arrays, read Valdes
    - Valdes, L. G., Proc. I.R.E., 42, pp. 420-427 (February 1954)
- Have fun, but be careful how much voltage the instruments might use to produce the currents they want to see.
    - This applies only to high resistance measurements.



## References:

**Extension of van der Pauw's theorem for measuring specific resistivity in discs of arbitrary shape to anisotropic media**
W L V Price 1972 *J. Phys. D: Appl. Phys.* **5** 1127-1132

**Abstract.** Van der Pauw (1958) has described a method of measuring electrical resistivity in discs of arbitrary shape based on a theorem which is applicable to samples of isotropic material. In this paper the theorem has been shown to be applicable also to samples of anisotropic material, and it is shown that it measures the geometric mean of the principal components of the resistivity tensor in the plane of the sample.
An isotropic body may be regarded as the special case of an anisotropic one in which the principal components of the resistivity tensor are all equal. It follows that van der Pauw's method may be applied to any material, and that it always measures $(\rho 1 \rho 2)^{1/2}$, where $\rho 1$ and $\rho 2$ are the principal components of the resistivity tensor in the plane of the sample.
Print publication: Issue 6 (June 1972)

Valdes, L. G., Proc. I.R.E., 42, pp. 420-427 (February 1954)

Smits, F. M., "Measurements of Sheet Resistivity with the Four-Point Probe," BSTJ, 37, p. 711 (1958).