

Understanding and Measuring Electrical Resistivity in Conductive Inks and Adhesives

from SGIA Journal (June 2000 Edition)

Before you can effectively make and operate membrane switches and other additive type circuits, you need to know the variables that affect their ability to conduct electricity.

Basic Electrical Concepts

Electricity is produced by the flow of electrons between atoms in matter. Some materials, such as metal, allow electrons to flow easily from atom to atom. These materials are called conductors.

Often, the analogy of a water pump connected to a pipe is used to illustrate electricity moving through a material or circuit. When the pump is off, water does not move through the pipe. When the pump is turned on, it exerts a force on the water that causes the water to move. If the water pipe is capped, no amount of force from the pump will cause the water to move through the pipe. However, if the cap is removed, or the end of the pipe is connected back to the inlet of the water pump, then water will flow through the pipe. If the pump applies more force, a larger volume of water will flow through the pipe in a given time.

In an electrical circuit, there must be a force acting on electrons to cause them to flow. We call this force the electromotive force (emf). A voltage source, such as a battery, has a positive terminal (+) and a negative terminal (-). Similar to the water pump, when the negative terminal of the battery is connected to a conductive material, it will apply a force (emf). Since like electrical charges are repelled, the free electrons on the atoms of the conductor, which are also negatively charged, will want to move away from the negative terminal on the battery. However, just like the capped water pipe connected to a water pump, if there is no place for the electrons to go, then they will not move through the conductor. If both the negative terminal and positive terminal from the battery or voltage source are connected to the conductor, then the electrons will be repelled away from the negative terminal and move toward the positive terminal. The greater



*by Don Banfield,
Product Manager and Co-
Founder
Conductive Compounds, Inc.*

Surface Resistivity Spectrum

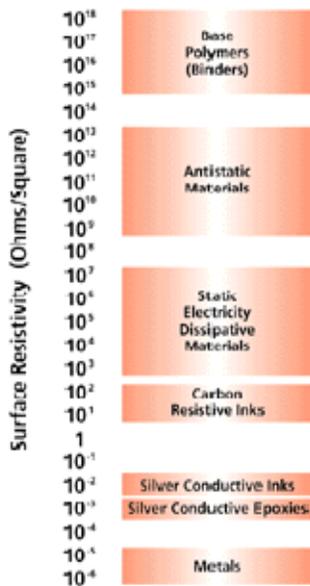


Figure 1

Comparison of Flake vs. Spherical Conductive Particles

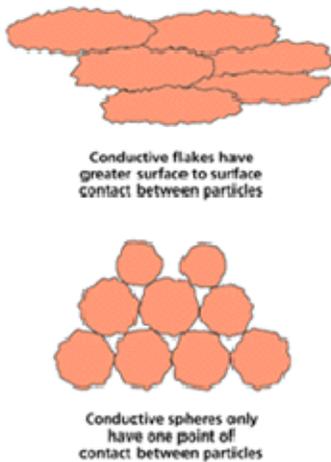


Figure 2

the emf exerted at the negative terminal, the faster the electrons will move. This emf is referred to as voltage. It is important to understand that this emf or voltage exists at the source; it does not move or flow through the material. It is the electrons in the material or circuit that flow in response to the voltage, similar to the water flowing through the pipe in response to a force exerted by the pump.

The rate at which electrons flow in response to a voltage is referred to as current, which is a measure of the amount of electrical charge moving past a point in a given time. As the emf or voltage is increased, the current will increase.

In our water pump and pipe example: What would happen if we kept the pump running so that it applied the same force, however, we switched from a large diameter pipe to a smaller diameter pipe? There would be less volume of water flowing through the pipe in a given time because the smaller pipe would restrict the water from flowing. Similarly, if we were to crimp the pipe to a small opening at one point, or allow mineral scale to build up on the inside surfaces of the pipe so that the friction increased on the pipe surface, we would provide resistance to the flow of water.

In an electrical circuit, resistance is the opposition to the flow of electrons through a material in response to an applied voltage. Conductors, such as metals, have very small resistances and allow electrons to flow easily if a voltage is applied. Insulators, such as plastics, have large resistances and do not allow electrons to flow easily.

In our water pump example, if minerals build up on the inside edges of the pipe so the surface is roughened and the opening in the pipe is narrowed, then the pump must exert more force if we want the same volume of water to flow in a given unit of time. In an electrical circuit, when there is increased resistance, more voltage is required to maintain the same current.

The relationship between current, voltage and resistance in a conductor such as solid metal is given by Ohm's Law:

$$I = E/R$$

WHERE:
I is the current measured in amperes
E is the voltage measured in volts
R is the resistance measured in ohms

The relationship between I, E and R in Ohm's Law is linear only in solid conductors such as metals.

In order to compare how easily one material will conduct electricity relative to another material, we measure the resistance of the materials. To do this, we use a device called an ohmmeter. When an ohmmeter is connected to a material, it applies a voltage and then measures the current through the material at the given voltage. Because resistance is inversely proportional to current according to Ohm's Law, an ohmmeter is calibrated to convert the measured current (amperes) to a resistance (Ohms or Ω). A lower resistance means that a material will conduct electricity more easily than a material with a high resistance.

Early scientists (including Ben Franklin) incorrectly assumed that electricity resulted from positively charged particles moving through a conductor. They therefore designated that electricity flowed away from the positive terminal of a battery through a conductor to the negative terminal of a battery. We still use this designation, called conventional current, even though the reality is that the flow of electrons is from the negative terminal to the positive.

Electrical Conductivity in Materials

In electronic circuits, there must be conductive paths between voltage sources and devices such as light emitting diodes (LEDs). In traditional rigid and flex circuits, solid metals such as copper are used for the conductive paths and solid metal solder is used to attach components to the conductive paths. In additive circuits, such as membrane switches and touch screens where the conductive layers are built up on a substrate, polymer-based electrically conductive inks are used to make the conductive paths and polymer-based electrically conductive adhesives are used to attach components to the conductive paths. Because mylar film is used as a substrate for membrane switches, traditional metal solder materials cannot be used due to the high temperature required to melt the solder, and the conductive paths made from polymer based inks are not solderable in most cases.

The adhesives and inks used for these applications contain two components: a plastic polymer binder and a conductive filler. The binder is used to hold the conductive filler particles together and to make the conductive filler stick to the substrate.

In conductive inks, the binder is usually a thermoplastic material. Thermoplastics are solid materials that can be dissolved in solvent or heated until they melt to turn them into liquids. The only purpose for the solvent in an ink system is to turn the thermoplastic binder into a liquid so the fillers can be mixed in and it can be screen printed. Once the solvent is evaporated or the thermoplastic is allowed to cool, the thermoplastic will turn into a solid once more. It can then be melted or dissolved again. For this reason, binders in solvent-based inks cannot withstand high temperatures or exposure to some solvents once they are applied and dried.

The polymer binder in most conductive adhesives is a thermoset. A thermoset differs from a thermoplastic in that it undergoes a chemical reaction when heat is applied that causes the thermoset to crosslink or harden. Once the thermoset hardens, it cannot be converted back into a liquid. For this reason, thermosets are generally much more resistant than thermoplastics to solvents and high temperatures once they harden. Most thermosets used for conductive adhesives are epoxies. There are two

Percolation Point

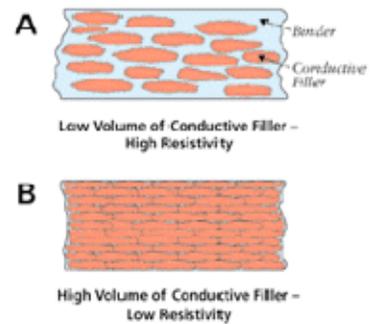
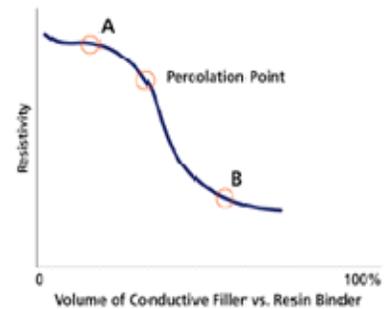


Figure 3

Percolation Point In Solvent Based Inks

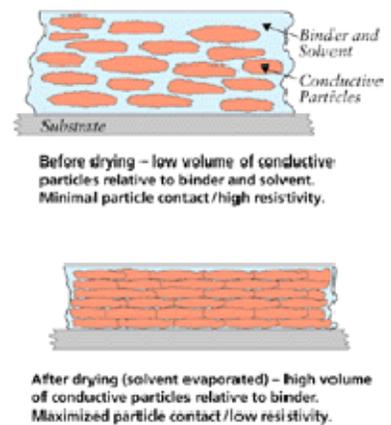


Figure 4

general types of epoxy adhesives; two part and one part. In a two-part conductive epoxy adhesive, the "A" component contains the epoxy polymer and the silver powder. The "B" component is a chemical that, when mixed with the epoxy adhesive, will cause the crosslinking chemical reaction to start. This chemical reaction is accelerated by heat. One component epoxy systems are pre-mixed materials where the chemical reaction between A and B is very slow at room temperature, but increases rapidly when high heat is applied to the adhesive.

The vast majority of conductive adhesives and inks use silver as the conductive metal filler. Less expensive but highly conductive metals such as copper work well in adhesives and inks initially, but the resistance will increase greatly over time. The reason for this is that all metals oxidize when exposed to oxygen in air and moisture, and other oxidizing agents. The metal oxide starts to build up on the surface of the metal. The most common example of this is rust, which is iron oxide, forming on the surface of metals that contain iron. In most metals, this surface metal oxide layer is not very conductive. Silver and

The vast majority of conductive adhesives and inks use silver as the conductive metal filler. Less expensive but highly conductive metals such as copper work well in adhesives and inks initially, but the resistance will increase greatly over time.

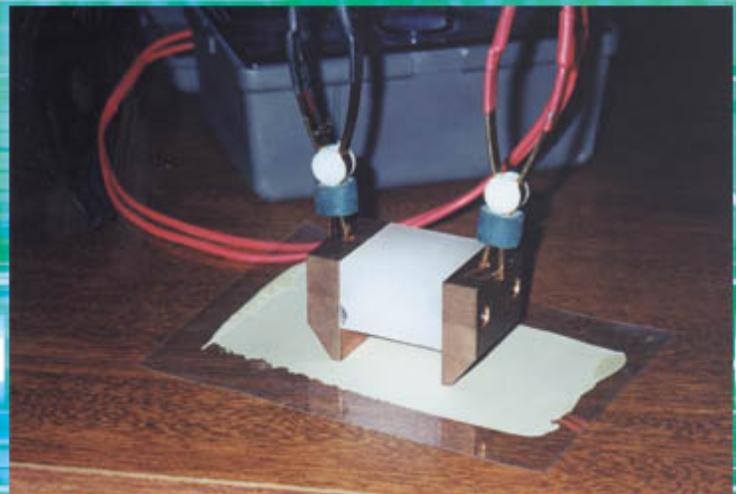
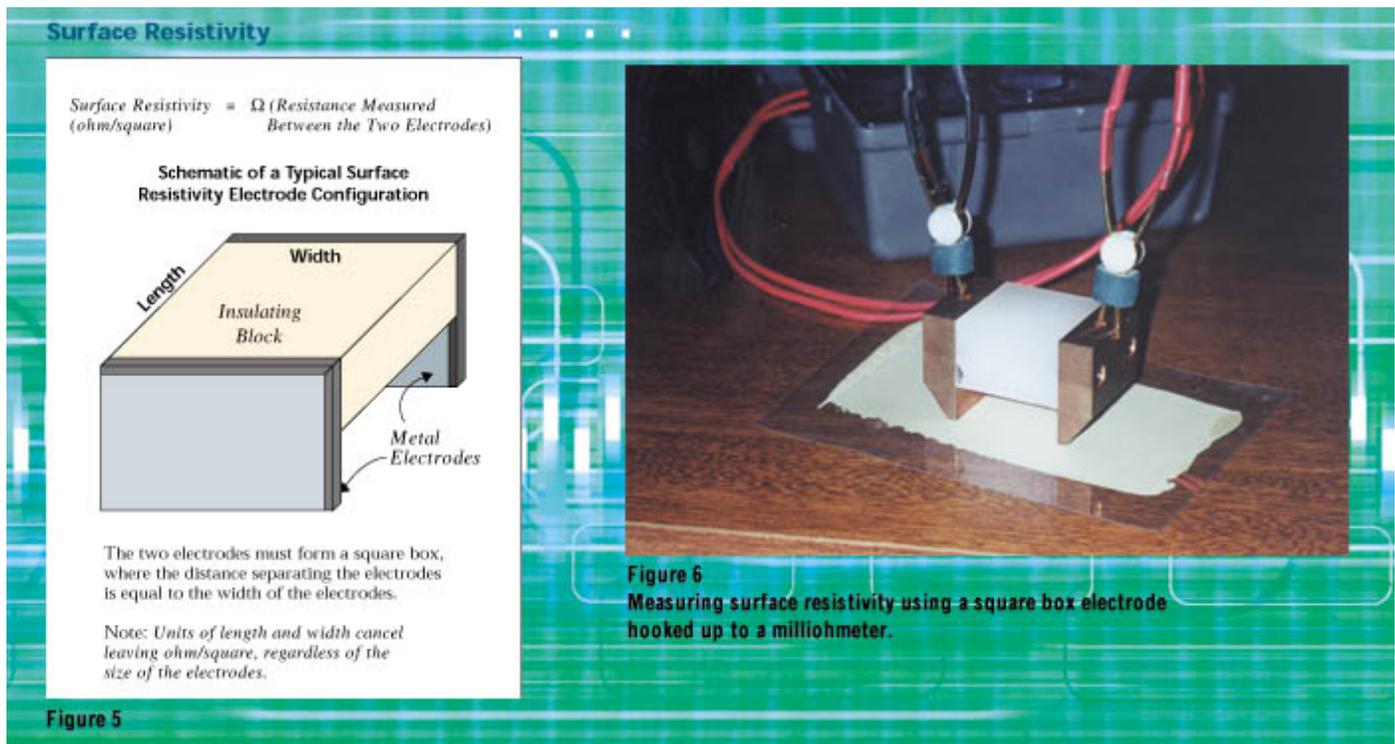
gold generate metal oxide layers that are very conductive. Carbon powder is used as the conductive filler in most polymer-based resistive inks.

Polymer-based conductive adhesives and inks have a much higher resistance than solid metals. Figure 1 shows the range of resistance (or resistivity) for different materials from insulators such as plastics to conductors such as metals.

This higher resistance in conductive inks and adhesives as compared to pure metals is due to the fact that even though an electron will flow easily through a metal particle, it encounters tremendous resistance when it has to jump from one

metal particle to another. Even if the metal particles are pressed together tightly, the resistance to cross the gap between the particles is high compared to the resistance within the metal particles themselves. Given the fact that electrons must travel across thousands of the particle to particle gaps in a metal-filled ink or adhesive, it is easy to see why the resistance is much greater than the resistance of a solid metal.

In order to minimize the resistance in a conductive ink or adhesive, it is crucial to optimize the amount of surface contact area between metal particles. Earlier versions of silver inks and adhesives used metal spheres as the conductive filler. When these spheres touch one another, there is only one very small point of contact between the particles (see Figure 2). In order to increase the area of contact between particles, a flattened metal flake configuration is often used. When the flakes nest together, there is much greater surface contact between particles, and more paths available for electrons to move from particle to particle.



Another phenomenon which contributes to the conductivity of polymer-based conductive inks and adhesives is the percolation point. As noted earlier, a plastic polymer binder has a very high resistance. If we add a small amount of highly conductive metal filler to the binder, the resistance will not change, since the metal particles will have large gaps between them. As we continue to add metal filler to the binder, the resistivity will remain high until we reach a point where some of the metal particles start to contact one another. After this point, the percolation point, adding a small amount of metal filler will produce a rapid drop in the resistivity of the ink or adhesive (see Figure 3). If we continue to add metal filler, we will eventually reach a point where the resistivity levels off, and increased loading of metal filler will not improve the conductivity of the ink or adhesive. In fact, higher loadings of filler beyond this point will start to degrade the adhesion and scuff resistance properties of the ink and can actually start to increase the resistance of the material as the conductive particles are not able to nest together efficiently. Good formulations of inks and adhesives will use an optimal flake configuration at a loading toward the bottom of the percolation point curve.

In most conductive inks and epoxies, the liquid materials as supplied will not have low resistivity. This is due to fact that when the solvent remains in the ink, there is a large gap between the silver particles. As the solvent evaporates, the volume of metal filler relative to the binder starts to increase, until the metal flakes finally make contact and the system becomes conductive (see Figure 4). Similarly epoxy adhesives generally shrink slightly as they crosslink or harden, and pull the flake particles closer together. It is essential that conductive inks be dried completely and conductive epoxy adhesives be crosslinked completely in order to minimize resistance. Even a small amount of residual solvent in an ink system can dramatically increase the resistance, as shown in the percolation point curve in Figure 3.

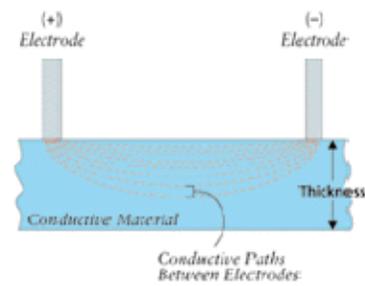
Measuring Resistivity to Compare Materials

In order to compare materials with respect to their abilities to conduct electricity, we measure the resistance in these materials. On a completed membrane switch, we can place the positive and negative probes of an ohmmeter on a screened and dried ink trace and measure the resistance in ohms from one point to another. Generally most manufacturers of membrane switches specify that all conductive paths must be 100 Ω or less point to point. Short of screening identical patterns for all materials we wish to evaluate, how can we compare materials?

There are two methods of evaluating resistance in materials: surface resistivity (sometimes called sheet resistivity) and volume resistivity.

With surface resistivity, we attempt to measure the resistance across the top layer of a conductive material. This is accomplished by placing two electrodes (positive and negative) connected to an ohmmeter on the surface of a screened sheet of conductive material so that both electrodes contact the material across the electrodes' entire length (see Figures 5 and 6). It is essential that both electrodes make intimate contact with the surface of the material. Usually a weight is applied to the top of the electrodes to press them into closer contact with the material surface. The material surface must be smooth and free of bumps and voids. The electrodes used are in a square box configuration, and the length of the electrodes must be exactly the same as the distance separating the inside surfaces of the electrodes. The electrodes in effect form opposite sides of a square. When surface resistivity is measured in this fashion, the resistance is read off the ohmmeter as Ohms/Square. Because the width separating the electrodes is identical to the length of the electrodes,

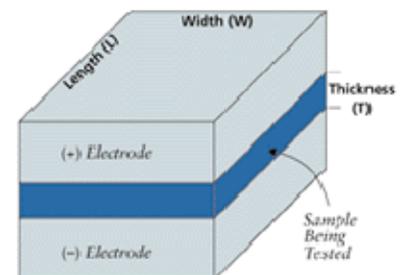
Surface Resistivity In Highly Conductive Materials



Resistivity In Electrically Conductive Materials Is Not Just a Surface Phenomenon

Figure 7

Volume Resistivity

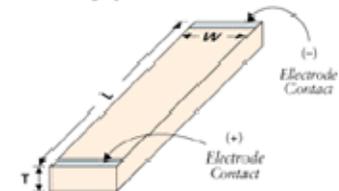


$$\text{Volume Resistivity} = \frac{\Omega \times A}{T} = \frac{\Omega \times W \times L}{T}$$

(Ohm-cm)

Where: Ω = Electrical resistance through the sample
 A = Area of the electrode face (cm²)
 L = Length of the electrode (cm)
 W = Width of the electrode (cm)
 T = Thickness of the sample (cm)

Measuring Volume Resistivity of Highly Conductive Materials



$$\text{Volume Resistivity} = \frac{\Omega \times A}{L} = \frac{\Omega \times W \times T}{L}$$

(Ohm-cm)

Where: Ω = Electrical resistance through the sample
 L = Length of the sample strip (cm)
 W = Width of the sample strip (cm)
 T = Thickness of the sample strip (cm)

Figure 8

the dimensions cancel out whether it is a one-inch electrode or a one-centimeter electrode and the surface resistivity becomes Ohms/Square if the electrode configuration is a perfect square.

Surface resistivity is a more precise measurement when dealing with insulating or slightly conductive materials, such as antistatic coatings on the surface of insulating materials, using low voltages. The problem with evaluating surface resistivity in highly conductive materials is the underlying assumption that electrons move from the negative electrode across the top surface of the conductive layer only to the positive electrode. As illustrated in Figure 7, the movement of electrons is not just a surface phenomenon. Even though the majority of the electrons will take the shortest path between the two electrodes, some electrons will travel through the cross section of

the conductive layer to move from electrode to electrode.

Most test methods minimize this effect by specifying a precise printed thickness for the conductive material before the surface resistance measurement is made. While this does not eliminate the volume effect, it does standardize the effect from sample to sample.

The other method for evaluating resistivity, volume resistivity, gives a more accurate portrayal of how conductive one material is relative to another. Instead of treating the movement of electrons as a surface phenomenon only, volume resistivity measures the resistance through a cross sectional volume of a given material. Typically, a sheet of material is placed between two electrodes of identical

surface area, and the resistance is measured through the material (see Figures 8 and 9).

Once the resistance is obtained, the volume resistivity is calculated using the following formula (Figure 8):

$$\text{Volume Resistivity} = (\text{Ohm-cm})$$

$$\frac{(\text{Ohms}) \times (\text{Electrode Area})}{\text{Thickness}} =$$

$$\frac{(\text{Ohms}) \times (\text{Length}) \times (\text{Width})}{\text{Thickness}}$$

Where the length, width and thickness are in centimeters

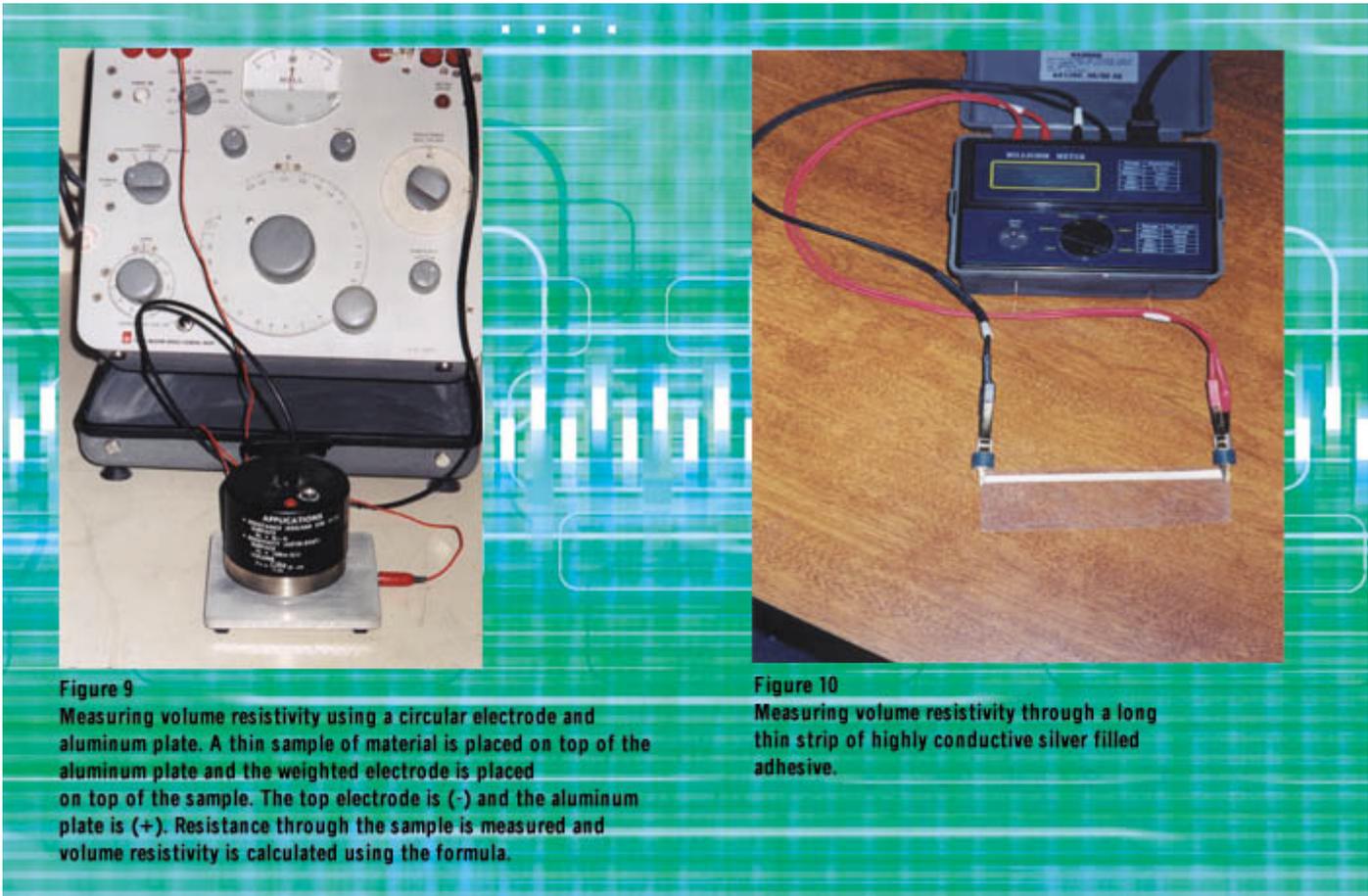


Figure 9
Measuring volume resistivity using a circular electrode and aluminum plate. A thin sample of material is placed on top of the aluminum plate and the weighted electrode is placed on top of the sample. The top electrode is (-) and the aluminum plate is (+). Resistance through the sample is measured and volume resistivity is calculated using the formula.

Figure 10
Measuring volume resistivity through a long thin strip of highly conductive silver filled adhesive.

With insulating or slightly conductive materials, this test configuration is very accurate. With highly conductive materials, the internal resistance of such a large surface area of conductive material is so small relative to the thickness that it can be difficult to obtain accurate resistance readings.

In order to overcome this, another accepted practice for measuring volume resistivity of highly conductive materials is to screen or coat a sample of the conductive material in a long, narrow line (Figure 8). Typically, a strip 6 inches (15.2 cm) long by 0.25 inches (0.64 cm) wide and .001 inch (.0025 cm) thick will be used.

With a sample in this configuration, we measure the resistance from one end of it to the other, making sure that the electrodes of the ohmeter bridge the entire width of the strip and make intimate contact with the sample (see Figure 10). To calculate the volume resistivity with this sample configuration, we use the formula above, with a few slight changes (Figure 8):

$$\text{Volume Resistivity} = (\text{Ohm-cm})$$

$$\frac{(\text{Ohms}) \times (\text{Electrode Area})}{\text{Sample Length}} =$$

$$\frac{\text{Sample Thickness} \times \text{Sample Width}}{\text{Sample Length}}$$

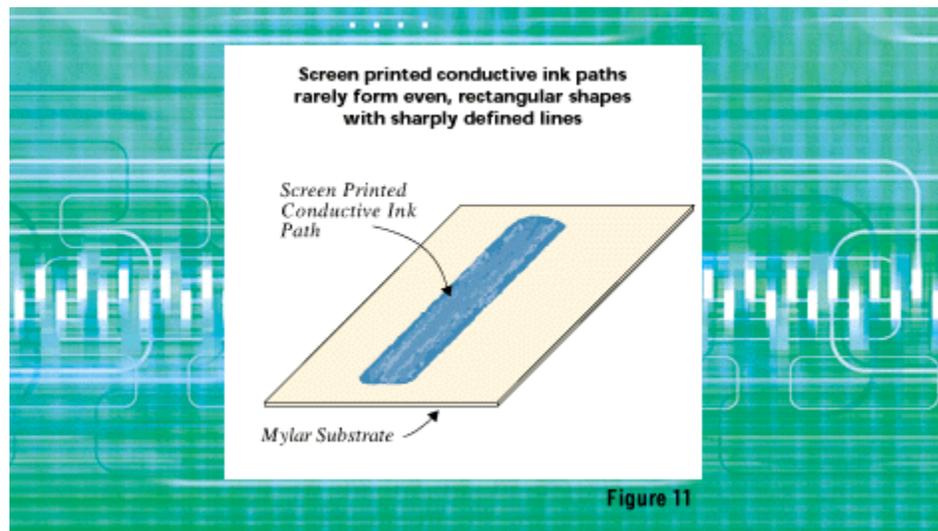
The question often comes up regarding how to convert a surface resistivity value to volume resistivity or point to point resistance on a conductive path.

Unfortunately there is no way to accurately convert a surface resistivity value to volume resistivity or vice versa.

With conductive epoxy adhesives, this sample strip can be prepared easily by carefully spacing two strips of clear adhesive tape 0.25 inches apart onto mylar film, and smoothing down the tape with a sharp metal edge to carefully remove air bubbles and bumps. Once the tape is in place, the conductive epoxy is placed in the gap between the two pieces of tape and, using a razor blade tilted at a shallow angle as a squeegee, the epoxy is slowly drawn down until it fills the gap

between the adhesive tape pieces consistently and smoothly. Carefully strip up both pieces of tape, and after placing the material in a heated oven to crosslink it, you are left with a long narrow strip of adhesive suitable for testing. Carefully measure the length (distance between electrodes), thickness of the sample and width of the sample, all in centimeters. Make sure that the sample is smooth and uniform in thickness and width.

Using clear adhesive backed tape to prepare a thin strip of solvent-based conductive ink is more difficult, as the solvent will dissolve the adhesive on the tape and allow conductive ink to wick in under the tape. Sample strips of conductive ink are best prepared by coating or screening a wide path of the ink onto mylar, then precisely cutting a



0.25 inch wide strip of mylar and conductive ink for measuring.

The question often comes up regarding how to convert a surface resistivity value to volume resistivity or point to point resistance on a conductive path.

Unfortunately there is no way to accurately convert a surface resistivity value to volume resistivity or vice versa.

Since surface resistivity indicates the resistance across the surface of a square box of conductive material, an approximate correlation can be made between a surface resistivity value and the point-to-point resistance of a printed conductive trace. Suppose we had a conductive trace that was 0.040 inches wide and 4 inches long. If we imagined that 4-inch-long path being broken down into interconnected square boxes 0.040 inches wide by 0.040 inches long, there would be 100 such square boxes on the conductive path (4 inches/0.040 inches = 100). Since the surface resistivity is always the resistance across a square box of material, we can take the surface resistivity of a given conductive material (in ohms/square) and multiply it by the 100 square boxes along our 4 inch by 0.040 inch conductive trace to find out the total resistance from one end of the trace to the other.

For example, suppose we had a conductive silver ink with a surface resistivity of 0.10 Ω /Square. Provided that our 4-inch long by 0.040-inch wide conductive path was the same thickness as the ink sample we obtained the surface resistivity from, and the conductive path was uniform in width and thickness and free of voids or contaminants, we could estimate the total resistance from one end of the conductive path to the other.

We already determined that this path would be composed of 100 square boxes measuring 0.040 inches by 0.040 inches. The surface resistivity across the surface of one of these square boxes would be 0.10 Ω /Square using this conductive ink. Therefore the total resistance from end to end on this

trace would be 0.10 Ω /Square x 100 squares = 10 Ω .

This value is a good approximation, but designers need to be cautious about relying on this conversion when extreme accuracy is needed.

One factor that can produce erroneous results when trying to establish a correlation between surface resistivity and total resistivity along a screen printed conductive trace is that when we try to apply a surface resistivity value to a long trace, we are incorrectly assuming that the electrons are travelling across the surface of the conductor only, and not through the entire cross sectional volume of the conductor. Another factor is that the screen printed trace will not be a perfectly defined path with sharp edges, widths and thicknesses (see Figure 11). Just like the water pump and restricted pipe example we used earlier, any variations in conductive path volume such as thickness variations, rounded corners and voids or contaminants along the path will increase the resistance to the flow of electrons, and make it more difficult to predict the total resistance of the path using the surface resistivity of the conductive ink.

A new test method for performing this correlation has been prepared by the Membrane Switch Council of the SGIA. This test method, ASTM F1896-98 (Test Method For Determining The Electrical Resistivity Of A Printed Conductive Material), does an excellent job of dealing with minimizing the factors that could lead to inaccuracy when converting surface resistivity of a conductive ink to point to point resistance on a conductive path.

Designers are cautioned to verify the results of any correlation between surface resistivity of a conductive ink and point-to-point resistance on a conductive path with an actual circuit build. Maintaining tight process controls in production to minimize voids, contamination and thickness variation will greatly minimize variations in point-to-point resistance on

conductive paths, especially when dealing with carbon resistive inks or silver/carbon ink blends where close tolerances on resistance are needed on the conductive paths.

Below is a partial list of some test methods for measuring resistivity/conductivity in materials to use as a reference.

SPECIFICATION	DESCRIPTION
ASTM F 1896-98	Test Method For Determining The Electrical Resistivity Of A Printed Conductive Material
ASTM D 4496	DC Resistance Or Conductance Of Moderately Conductive Materials
ASTM D 257	DC Resistance Or Conductance Of Insulating Materials
ASTM D 991	Volume Resistivity Of Electrically Conductive And Antistatic Products
ASTM D 2739 90	Volume Resistivity of Conductive Adhesives

Conclusion

Electrically conductive adhesives and inks are crucial to the manufacturing and long term operation of membrane switches and other additive type circuits. Understanding how these materials conduct electricity and the variables that affect their ability to conduct electricity helps when trying to minimize resistance or reduce the circuit to circuit variation in resistance between voltage sources and devices.

Two methods of evaluating resistivity in conductive materials are surface resistivity and volume resistivity. There is no way to establish a direct correlation between values obtained using these two methods, and using surface resistivity to predict point to point resistance on a conductive path will provide a good estimate, but results should always be verified on an actual manufactured circuit.