

# Characterization of Conductors for Printed Electronics

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Recently, there has been a lot of attention focused on the advancing field of printed electronics. Many analysts predict that the printing of electronic devices will be the next giant step in the evolution of electronics manufacture. Items that previously only existed as an assemblage of discrete components and partially integrated circuits are now on the verge of being manufactured into fully integrated devices using conventional printing techniques at a fraction of the costs associated with traditional manufacturing processes. Transistors, photovoltaics, displays, lighting, power, memory, sensors, and mechanical actuators all exist now in printable forms. But to manufacture nearly any printed electronic device will still require the use of one of the oldest of printable electronic materials, the printable conductor. It's the goal of this paper to discuss how to characterize a printed conductor and to identify the differences between the properties that derived from the material, and the properties that are derived from the deposition process.

## Resistance and Resistivity

It's important to understand the differences between resistance and resistivity when describing a printable conductor (a.k.a. conductive ink). Two inks yielding equal resistance values for the same print may actually be delivering dramatically different performance. If one of the inks has actually been printed at half the film thickness of the other one, its performance is actually twice as good. Even if this ink costs 50% more than the other ink, its ultimate cost of use will be 25% cheaper to achieve the same product spec. To accurately assess the real price/performance relationship for conductive inks, resistance measurements are not sufficient. Resistivity is the metric that describes the true performance of a conductor. Both resistance and resistivity will be described in detail in the following paragraphs.

*Resistance* is a measure of the degree to which an object opposes an electric current through it and is measured in ohms ( $\Omega$ ). Resistance values measured for conductors will vary according to the material itself, as well as to the length, width, and thickness of the material. It's intuitive that copper is a better conductor than wood, that a longer wire will have more resistance than a shorter wire, and that a thicker wire will have less resistance than a thinner wire of equal length, but how are these differences properly expressed? The resistance of a system depends both on the geometry of the system being measured, and the nature of the material itself. The electrically resistive nature of the material is an intensive property known as *resistivity*. The relationship between resistance and resistivity is expressed mathematically as:

**Eqn.1:**  $\rho = \frac{A}{L} R$

Where:

$\rho$  = volume resistivity

A = cross-sectional area

L = length

R = resistance

As can be seen by this equation, the resistivity of a material does not depend on the size or shape of the material (but may depend on other factors such as temperature). This allows us to directly compare materials on an equal basis. Note that eqn.1 depicts *volume resistivity*, since the volumetric units of area and length are used. Typical units for volume resistivity of conductors are  $\mu\Omega\cdot\text{cm}$  or  $\Omega\cdot\text{m}$ . Some common resistivity values are shown in table 1.

**Table 1 – Resistivities of common materials**

material	$\Omega\cdot\text{m}$	$\mu\Omega\cdot\text{cm}$
Silver	1.59E-08	1.59
Copper	1.72E-08	1.72
Gold	2.44E-08	2.44
Aluminum	2.82E-08	2.82
Nickel	6.99E-08	6.99
Brass	8.00E-08	8.00
Iron	1.00E-07	10.0
Tin	1.09E-07	10.9
Platinum	1.10E-07	11.0
Lead	2.20E-07	22.0
Mercury	9.80E-07	98.0
Carbon	3.50E-05	3500
Germanium	4.60E-01	4.60E+07
Silicon	6.40E+02	6.40E+10
Sulfur	1.00E+15	1.00E+23
PET	1.00E+20	1.00E+28
Teflon	1.00E+23	1.00E+31

Another common way to express resistivity is by:

**Eqn.2:**  $\rho_w = \frac{W}{L_1 L_2} R$

where:

W = weight of test specimen (i.e., the conductor being measured, minus any substrate)

$L_1$  = length between probes

$L_2$  = total length of test specimen

R = resistance

Note that eqn.2 depicts *weight resistivity*. Typical units for weight resistivity are ohms-gram/meter<sup>2</sup>. Note that the formulas for weight resistivity and volume resistivity only differ by the density of the material, since  $(W/L_2)/\text{density} = A$ .

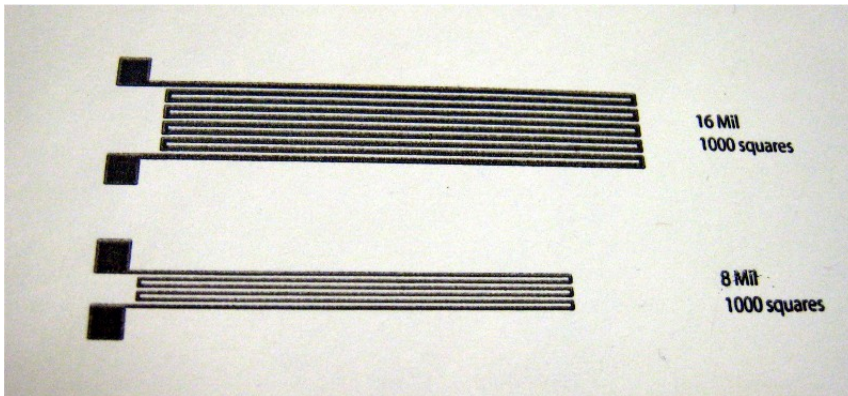
Therefore:

**Eqn.3:**  $\rho \cdot \text{density} = \rho_w$

### **Measuring Resistance and Resistivity**

Resistance is easily measured using only a \$20 ohm-meter which is accurate enough for many purposes, especially if the sample is prepared correctly. Care must be taken so that the measurement isn't too close to the resolution of the meter. Measuring a 0.5-ohm sample with an ohm-meter with a resolution of 0.1 ohms is obviously not a good measurement (more on this later). If the goal is to find out what the resistance of a fixed geometry is (such as in meeting a design spec), then a more precise meter will be required. However, if the goal for measuring resistance is to find out the resistivity of the material, then a longer, narrower sample can be made so that the resistance value is higher and the percent error is reduced. Since the length and width (or mass) of the sample are calculated out, changing them does not affect the result beyond its precision.

For measuring volume resistivity (eqn.1), the cross sectional area of the print will need to be determined. As such, this method is best applied to thicker conductors. If the conductor is thick enough, a micrometer can be used to determine its film thickness. However, even the thickest of printed conductors (screen printed) are often too thin to be measured with enough precision by a micrometer. Furthermore, micrometers can only measure the maximum thickness, and not the average. A profilometer is usually required to give an accurate measurement, which can directly measure the cross sectional area. Profilometers come in two variations, stylus and laser, with laser being the more precise of the two. Laser profilometers can also measure and integrate in 3 dimensions for more accurate overall results. When preparing a sample for measurement, it's important to try to keep the cross sectional area of the sample as constant as possible for good results. Long straight lines work the best, and can be folded into serpentines to fit better on substrates. Multiple cross sectional areas can be measured and averaged for better results.



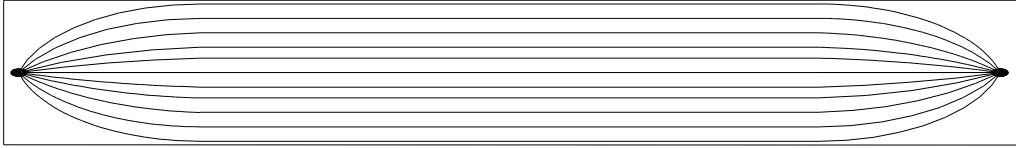
**Figure 1:** Serpentine used to characterize printed conductors

When printed films get very thin (typically under a micron), even laser profilometers have trouble providing good results. This is not because the resolution of the instrument is exceeded, but rather because the roughness or flatness of the substrate begins to become important. A 1-micron thick film on a paper substrate with 0.5 microns of roughness quickly disappears into the noise. Even relatively smooth polyester substrates can present problems due to very slight distortions created during the drying/curing process. For such a thin film, weight resistivity is the preferred method to determine resistivity. Eqn.2 shows that the weight of the conductor will need to be known. For printed conductors, the density of the substrate will also need to be known so that its weight may be calculated and subtracted out. When weighing the sample, a high precision balance is required (usually 0.1mg). Also, care must be taken to not let static electricity effect the weight measurement. Ionic discharge or special sample holders are usually sufficient to get accurate and repeatable weights.

### **Potential Errors in Measuring Resistance**

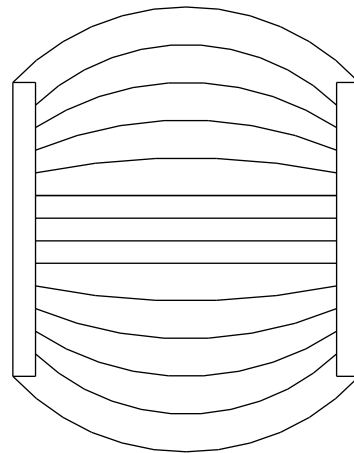
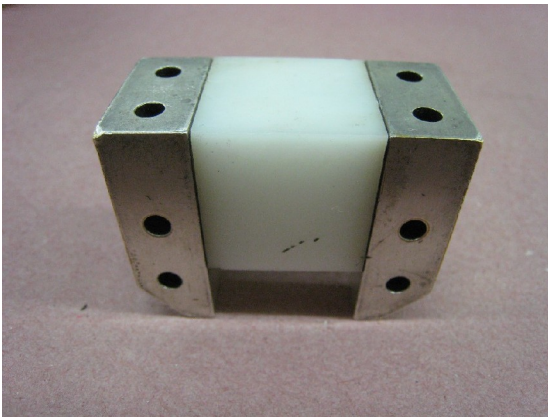
There are three types of potential errors in measuring the resistance of conductors:

1. Positive errors from increased current density. These errors result from the current not traveling through the entire conductor at the ends near point probes. Figure 2 shows how the areas near the probes pass no current, and are essentially “wasted”. The material appears to be more resistive than it actually is. These effects are minimized (and virtually eliminated) by making the conductor much longer than it is wide. Using probes that contact all the way across the sample also eliminate this error. Theoretically, the effect is also present in the Z-direction of the sample, but in practice, we are usually measuring very conductive thin films and such errors can be ignored. In general, the better the conductor, the more easily the current spreads, and hence the less error is measured.



**Figure 2.** Top view of current flow in 2 point probing of a conductive strip. End effects become negligible as the strip becomes longer.

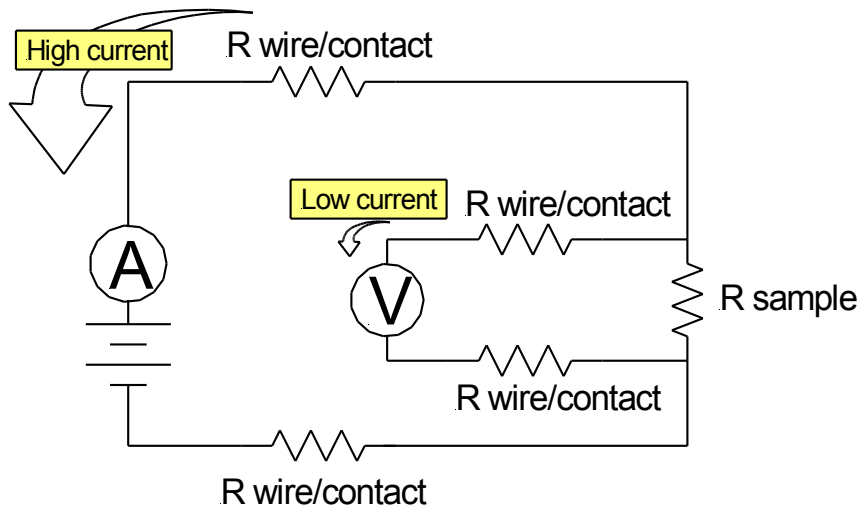
2. Negative errors from decreased current density. These errors occur when the geometry of a probe is used to define the sample boundaries. A classic example is the 1-square probe used to measure sheet resistance in ohms/square (more on this later). Figures 3a and 3b show this type of probe and the manner in which the current spreads beyond the boundaries defined by the probe. In this case, the material appears to be less resistive than it actually is. Note, that the better the conductor, the more easily the current spreads, and hence the greater the error is measured. This probe configuration is not recommended for good conductors such as silver ink.



**Figures 3a and 3b.** Side view of a “1-square probe” and the top view of current spread for that probe. This probe design is not recommended for measuring conductive inks.

3. Positive errors from contact and lead resistance. These errors result from the resistance of the test leads and contact areas between the leads and the sample acting in series with the sample itself. These errors are usually small in magnitude, and as a rule-of-thumb they are negligible for measurements over 1-ohm (depending on the measuring setup). However, for samples less than 1-ohm, an alternative measuring apparatus known as the 4-point (Kelvin) probe is required (see Figure 4). In its basic form, the measurement system is set up so that a low impedance outer loop drives a known current through the test sample.

A high impedance voltmeter is used on an inner loop to measure the voltage drop across the sample, but not the test wire or contact points. Since the inner loop is high impedance, current is low and the voltage drop across the inner series resistances is negligible. With an accurate voltage drop and current measured across the sample, Ohms law is used to calculate the resistance of the sample.



**Figure 4.** 4-point (Kelvin) probe

### Sheet Resistance, Sheet Resistivity, and Surface Resistivity

Anyone working with conductive inks has probably come across the phrase “ohms per square” at some point. The same is true for folks working with antistatic and static dissipative materials. However, there is a lot of confusion surrounding this phrase, which is technically (dimensionally) incorrect. Furthermore, it can be applied to both sheet resistance and sheet resistivity, and as such, is often misused and misunderstood.

*Sheet Resistance* is an extensive property that depends upon the film thickness of the conductor being measured. Sheet resistance is really nothing more than a restatement of volume resistivity without the film thickness being specified. Since it is an extensive property, care must be used when describing material performance with sheet resistance. Sheet resistance is no better at describing inherent conductivity/resistivity than a simple resistance measurement, but much like a simple resistance measurement, it can still be useful to determine if a printed conductor is meeting a specific performance spec. When film thickness cannot be easily determined, such as during a print run, sheet resistance can be used to estimate the material performance, particularly when a film thickness is assumed and a rough estimate of volume resistivity is generated. Sometimes in the conductive ink industry, “ohms per square” are the units given for volume resistivity, with an implied 1-mil film thickness. “Ohms per square per mil” is the “correct” term,

whose units are the same as volume resistivity when the imaginary units of “square” are ignored.

**For volume resistivity:**  $\frac{\text{ohms}}{\text{square} / \text{mil}}$  or  $\frac{\text{ohms} * \text{mil}}{\text{square}}$

**Eqn.4:**  $\frac{2540\mu \Omega \cdot \text{cm}}{\Omega / (\text{square} / \text{mil})} = 1$

*Surface resistivity*, also known as *sheet resistivity* is a pseudo-intensive material property that applies when the assumption that current can only flow at the surface of a material is valid. The proper units of sheet resistivity are ohms, but the technically incorrect units of ohms/square are often used. Surface resistivity can be directly measured when the thickness of the bulk material does not effect the resistance measurement at the surface. Examples of this include:

1. A doped semiconductor with a negligibly thin dopant layer.
2. A conductor measured at very high AC frequencies where skin effect occurs.
3. A highly resistive material with a conductive surface where the current flows almost entirely in the surface. An example of such a material would be a plastic made with free ethoxylated fatty amines. The ethoxylated fatty amines bloom to the surface where their hydroxyl groups engage in secondary bonding with atmospheric moisture to carry current. No significant current is carried through the resistive bulk of the material.

When these conditions do not apply, surface resistivity can still be estimated using a measuring apparatus that includes a guard electrode capable of compensating for current flow in the bulk of the material (see ASTM D-257). The units for surface resistivity are properly expressed in ohms (but are often given in ohms per square), which exacerbates the confusion between surface resistivity and sheet resistance.

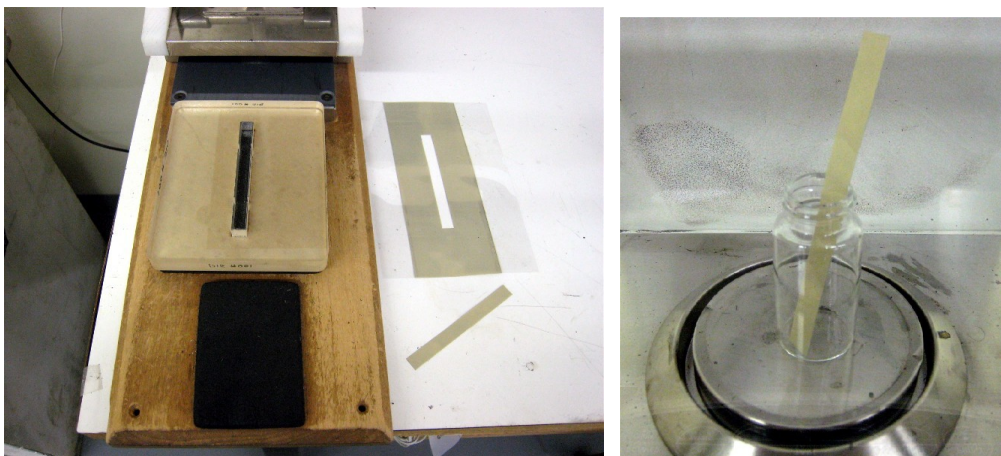
**Table 2: Nomenclature summary**

Property	Type	SI Units	Common units
Resistance	extensive	$\Omega$	$\Omega$
Sheet resistance	extensive	$\Omega$	$\Omega/\text{square}$
Volume resistivity	intensive	$\Omega \cdot \text{cm}$	$\mu\Omega \cdot \text{cm}, \Omega / (\text{square} / \text{mil})$
Weight resistivity	intensive	$\Omega \cdot \text{gram} / \text{meter}^2$	$\Omega \cdot \text{gram} / \text{meter}^2$
Sheet/surface resistivity	intensive (under the right conditions)	$\Omega$	$\Omega/\text{square}$

Intensive properties are physical properties of a system that do *not* depend on the system size or the amount of material in the system, where as extensive properties do.

## Measuring Resistivity at PChem Associates

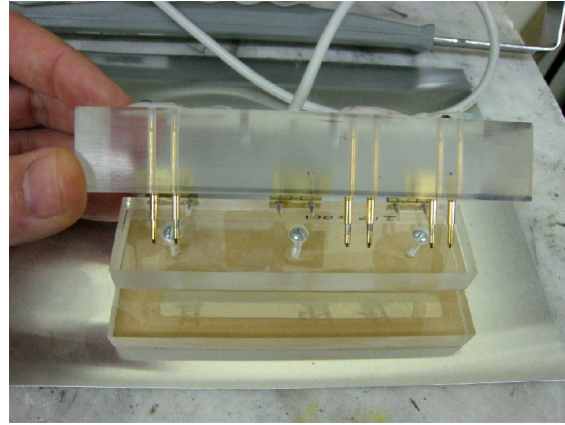
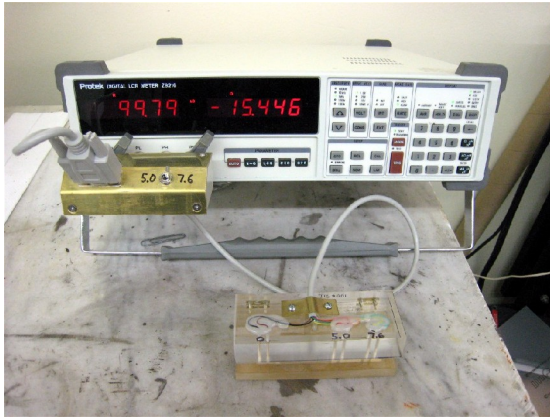
At PChem Associates, we measure weight resistivity almost exclusively. This is because the particles and inks we manufacture are based on nano technology. The small particle size combined with the high speed printing methods we typically employ (such as flexography) generally lead to dry film thicknesses on the order of 1-micron, which is at the lower limits of what profilometry can resolve without substrate noise and errors. Conventional flake based inks will yield much thicker depositions, even at the same viscosity with the same printing process. The reason for this is that a typical silver flake is itself 1-micron thick. When printed, multiple flakes will be stacked on top of each other leading to film thicknesses in the 3-5 micron range.



**Figures 5a and 5b** – Die cutter and sample holder for weight determination.

Figure 5a shows how the samples are prepared for measurement. The conductor is first printed onto a substrate using any number of methods, such as a commercial press, a Meyer rod, or a flexographic lab proofer. After being cured, a die cutter is then used to punch out a 1x10cm strip. The die cutter ensures accurate and repeatable measurements for the dimensions (and therefore weight) of the substrate and conductor. The strip is then weighed in the vertical position in order to minimize electrostatic interactions with the 0.1g balance. At these low masses, these interactions are not insignificant. Alternately, an ion generator can be used to neutralize the charge on the substrate.

A 4-point resistance meter is used in conjunction with a custom spring-pin jig to measure the resistance of the sample. Two spacings are provided for different length substrates, with a switch between the two. The spacing between the outer probes and the inner probes also allows for the current to spread to parallel field lines before voltage is measured, reducing the errors described in Figure 2.



Figures 6a and 6b – 4-point resistance measurement jig at PChem

### Example 1:

A 10cm x 1 cm sample of silver ink on a 5 mil polyester substrate has a weight of 0.1831g and a resistance of 0.512 ohms with an inner probe spacing of 7.6 cm. The sheet density of the polyester is 0.01753 g/cm<sup>2</sup>.

1. What is the weight resistivity of the sample?
2. What is the ratio of the sample's resistivity to bulk silver?
3. What is the estimated volume resistivity of the sample?
4. What is the estimated film thickness of the silver?

1. Equation 2 defines the weight resistivity as  $\rho_w = \frac{W}{L_1 L_2} R$ . Calculating the weight of the substrate and subtracting from the weight measured gives the weight of the silver film. Converting the length units to meters gives the result in SI units:

$$\rho_w = \frac{0.1831g - 0.1753g}{0.10m * 0.076m} * 0.512\Omega = 0.53 \text{ g}\Omega/\text{m}^2.$$

2. The weight resistivity of silver is 0.177g $\Omega$ /m<sup>2</sup>. 0.53/0.177 = 3.0x bulk silver.
3. The relationship between weight and volume resistivity is given as  $\rho \cdot \text{density} = \rho_w$ . The density of the printed silver is not the bulk density of silver, 10.5 g/cm<sup>3</sup> due to porosity inherent as a result of the drying and sintering process. An estimate of 80% of bulk silver density is used. Therefore

$$\rho = \frac{0.53\text{g}\Omega / \text{m}^2}{8400000\text{g} / \text{m}^3} = 6.3 \times 10^{-8} \Omega \cdot \text{m} = 6.3 \mu\Omega \cdot \text{cm}$$

Note that the value of 6.3  $\mu\Omega$ -cm is actually 4.0x bulk silver on a volumetric basis because of the density differences between silver ink and bulk silver. Because a customer is typically buying silver ink on a weight basis and not a volume basis, the comparative performance based on weight is generally more applicable.

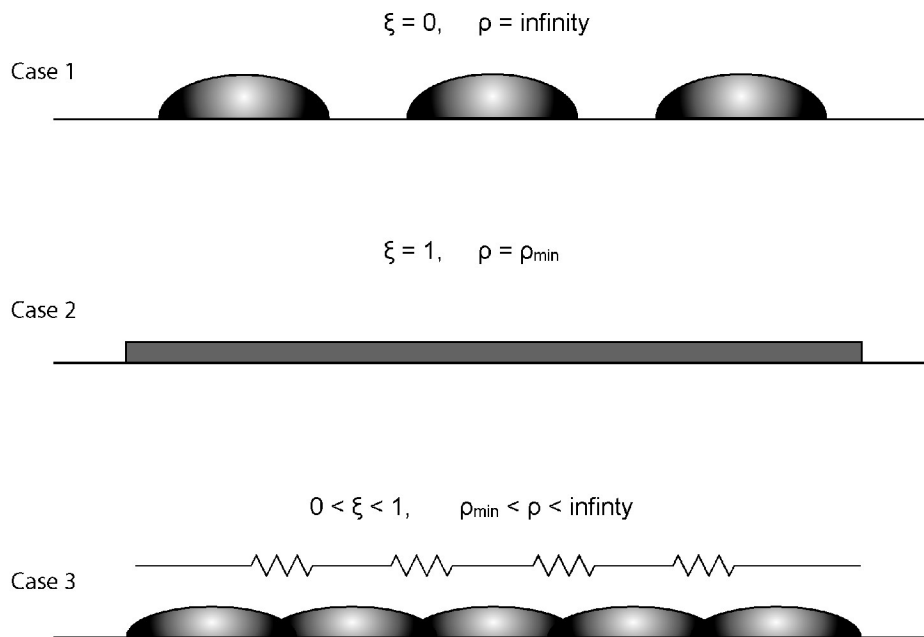
4. As in answer #1, the weight of the silver is 0.1831g-0.1753g = 0.0078g. From answer #3, the estimated density of the silver ink is 8.4 g/cm<sup>3</sup>. The area of the silver is 10cm<sup>2</sup>, so h=0.0078/(10\*8.4)=9.3\*10<sup>-5</sup>m = 0.93 microns.

## Print Efficiency

The last topic of discussion for this paper is print efficiency, a concept proposed by the author. Print efficiency is a dimensionless measure of how well the intrinsic conductivity of the printed conductor is utilized. It is the ratio of the resistivity performance of the printed ink versus the theoretical resistivity of the ink in a perfectly prepared sample.

$$\text{Eqn.5: } \xi = \frac{\rho_{\text{minimum}}}{\rho_{\text{measured}}}$$

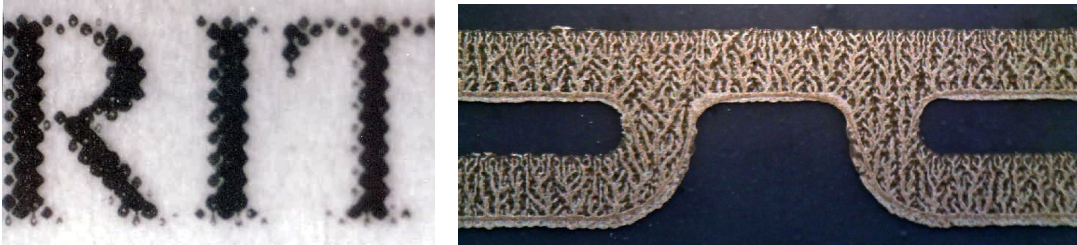
Figure 7 demonstrates how the measured resistivity differs depending on the quality of the printed film.



**Figure 7** – Print efficiency

Case 1 is an example of one extreme, where the print efficiency  $\xi=0$ . Although highly conductive material was deposited on the substrate, no conductivity is measured because islands of the material formed with no conductive bridges between them. Case 2 shows the other extreme, where  $\xi=1$ . A perfectly smooth and flat film of the same average cross sectional area was deposited, which has no bottlenecks to disrupt the flow of current. Case 3 depicts a real world example of what actually happens during the printing process. Thicker and thinner areas are left after the film is deposited and cured. The thinner areas are not capable of carrying as much current as the thicker areas without adding extra resistance. They can be modeled as resistors in series with good conductors, and these resistors disproportionately affect the measured resistance of the sample.

In actual practice, it is impossible to prepare a perfectly flat and planar sheet of silver, but efficiency numbers can still be generated between production samples versus better samples produced in a laboratory with multiple depositions smoothing out surface roughness and building up film thickness.



**Figures 8a and 8b** – Defects inherent in the gravure and flexographic printing processes.

Figure 8a shows how print efficiency can be affected by the gravure printing process. Gravure printing deposits ink from discrete cells engraved into a metal printing plate. If the ink from these cells does not flow completely together and level, print inefficiencies will be seen. Figure 8b shows inefficiencies from the flexographic printing process. In flexography, ink is transferred to a substrate from a raised area on an elastomeric printing plate. During the separation process, air infiltrates in between the solid/liquid/solid boundaries in order to displace the splitting ink film. This air infiltration results in random river like formations in a process known as viscous fingering. The net results are areas of thicker and thinner ink. Figures 8a and 8b show worst-case scenarios. There are many techniques used to minimize both of these effects in actual practice.

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