

Thin Film Surface Resistivity

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What is thin film surface resistivity?

Definition

Surface resistivity could be defined as the material's inherent surface resistance to current flow multiplied by that ratio of specimen surface dimensions (width of electrodes divided by the distance between electrodes) which transforms the measured resistance to that obtained if the electrodes had formed the opposite sides of a square.[1] In other words, it is a measure of the material's surface inherent resistance to current flow. Surface resistivity does not depend on the physical dimensions of the material. According to Ohm's law for circuit theory, the resistance of a material is the applied voltage divided by the current drawn across the material across two electrodes.

$$R = V/I \quad (1)$$

Where:

- R =Resistance (ohms, Ω)
- V = Voltage (volts,V)
- I = Current (amperes,A)

This electrical resistance is proportional to the sample's length and the resistivity and inversely proportional to the sample's cross sectional area.

$$R = \rho l/A \quad (2)$$

Where:

- ρ = Resistivity
- A =cross- sectional area
- l = length

Units

The physical unit for surface resistivity is ohms, Ω . Often in practice, surface resistivity is given in units of Ω/square . This unit should be seen as a logo but not as the physical unit of surface resistivity. Although, it is important to understand what Ω/square means because in most publications the surface resistivity unit is expressed that way.[2] Those who are not familiar with this term will ask, “Per square what?”, Inches? Feet? Yards? The answer would be: per any square, as long as the measurement is related to a square. Assume that the test sample has a rectangular shape with unit thickness (t). Then, equation 2 could be written as,

$$\rho = R \cdot wt/l = R w/l \quad (3)$$

Where:

w = width

l = length

The resistance of a square sample could be considered by analogy with an electric circuit to be a resistor with resistance R_0 as shown in Figure 1. According to equation 3, its resistivity would equal its resistance because $w = l$.

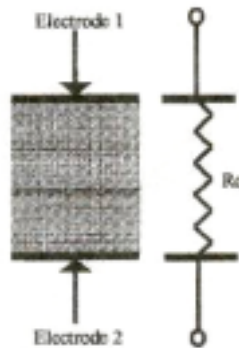


Figure 1: Square sample as a single resistor.

The resistance of a rectangular sample which length would be twice its width would be $2R_0$. This could be considered as two resistors R_0 connected in series, as shown in Figure 2.

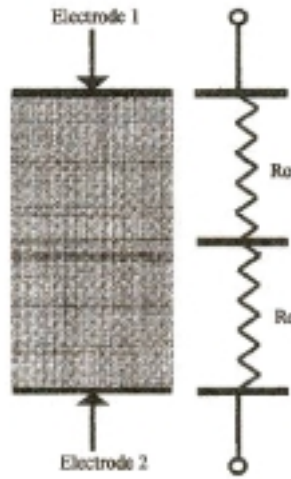


Figure 2: Square sample as two resistors in series

However, its resistivity would be R_0 because resistivity is a fundamental material property, which is independent of test sample dimensions.

$$\rho = 2R_0 w/2w = R_0$$

Similarly, the resistance of a rectangular sample with width twice its length will be $\frac{1}{2} R_0$ and could be considered as two resistors R_0 connected in parallel, as shown in Figure 3.

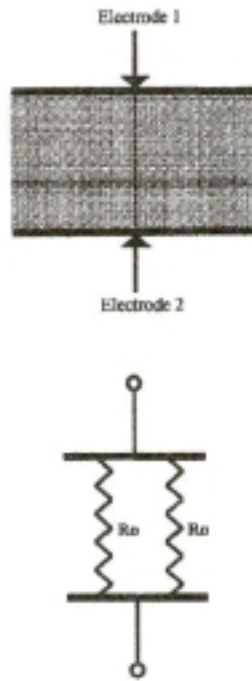


Figure 3: Square samples as two resistors in parallel.

Its resistivity it would be still expected to be R_0 .

$$\rho = \frac{1}{2} R_0 \frac{2l}{l} = R_0$$

It could be concluded that the surface resistivity of a test sample with unit thickness (t) is expected to equal the resistance of the sample in square dimension regardless of its in-plane dimensional surface term approximate resistance. The term surface resistivity in Ohms/square is the indication of this measurement calculation.

This section will outline methods for determining the surface resistivity of a material using common techniques such as the four-point probe method and the Van der Pauw method. Methods for measuring surface resistivity in polymers and advanced techniques developed for specific applications are also discussed.

Van der Pauw

The Van der Pauw technique, due to its convenience, is widely used in the semiconductor industry to determine the resistivity of uniform samples. [3,4] As originally devised by Van der Pauw, one uses an arbitrarily shape, thin-plate sample containing four very small ohmic contacts placed on the periphery, preferably in the corners, of the plate. A

schematic of a rectangular Van der Pauw configuration is shown in Figure 4.

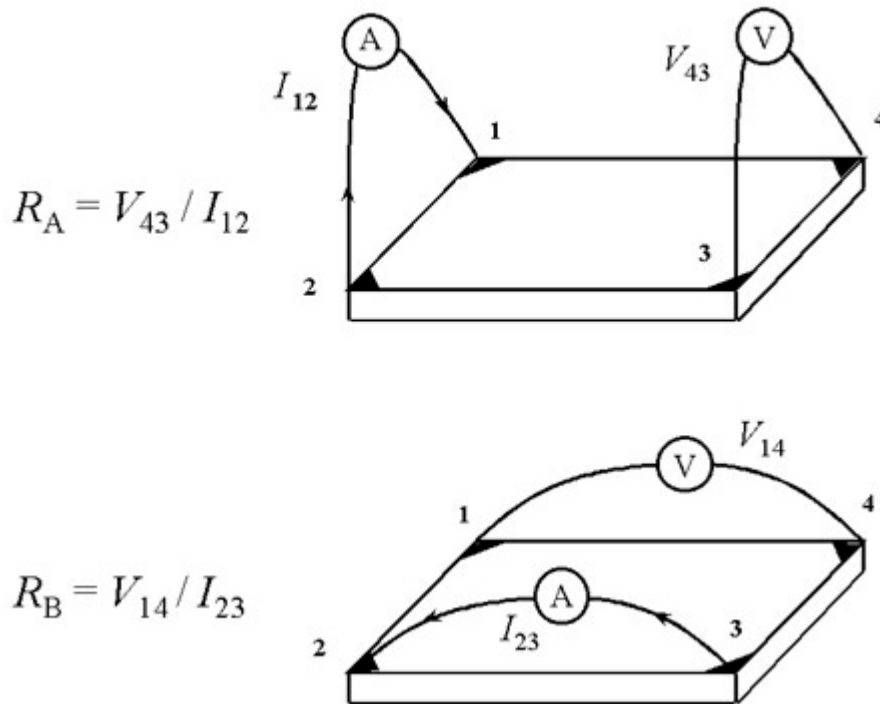


Figure 4: Schematic of a Van der Pauw configuration used in the determination of the two characteristic resistances R_A and R_B .

The objective of the resistivity measurement is to determine the sheet resistance R_s . Van der Pauw demonstrated that there are actually two characteristic resistances R_A and R_B , associated with the corresponding terminals shown in Figure 4. R_A and R_B are related to the sheet resistance R_s through the Van der Pauw equation:

$$\exp(-\pi R_A/R_s) + \exp(-\pi R_B/R_s) = 1 \quad (4)$$

which can be solved numerically for R_s .

The bulk electrical resistivity ρ can be calculated using:

$$\rho = R_s d. \quad (5)$$

To obtain the two characteristic resistances, one applies a dc current I into contact 1 and out of contact 2 and measures the voltage V_{43} from contact 4 to contact 3 as shown in Figure 4. Next, one applies the current I into contact 2 and out of contact 3 while measuring the voltage V_{14} from contact 1 to contact 4. R_A and R_B are calculated by means of the following expressions:

$$R_A = V_{43}/I_{12} \text{ and } R_B = V_{14}/I_{23}. \quad (6)$$

The objective of the Hall measurement in the Van der Pauw technique is to determine the sheet carrier density n_s by measuring the Hall voltage V_H . The Hall voltage measurement consists of a series of voltage measurements with a constant current I and a constant magnetic field B applied perpendicular to the plane of the sample. Conveniently, the same sample, shown again in Figure 5, can also be used for the Hall measurement.

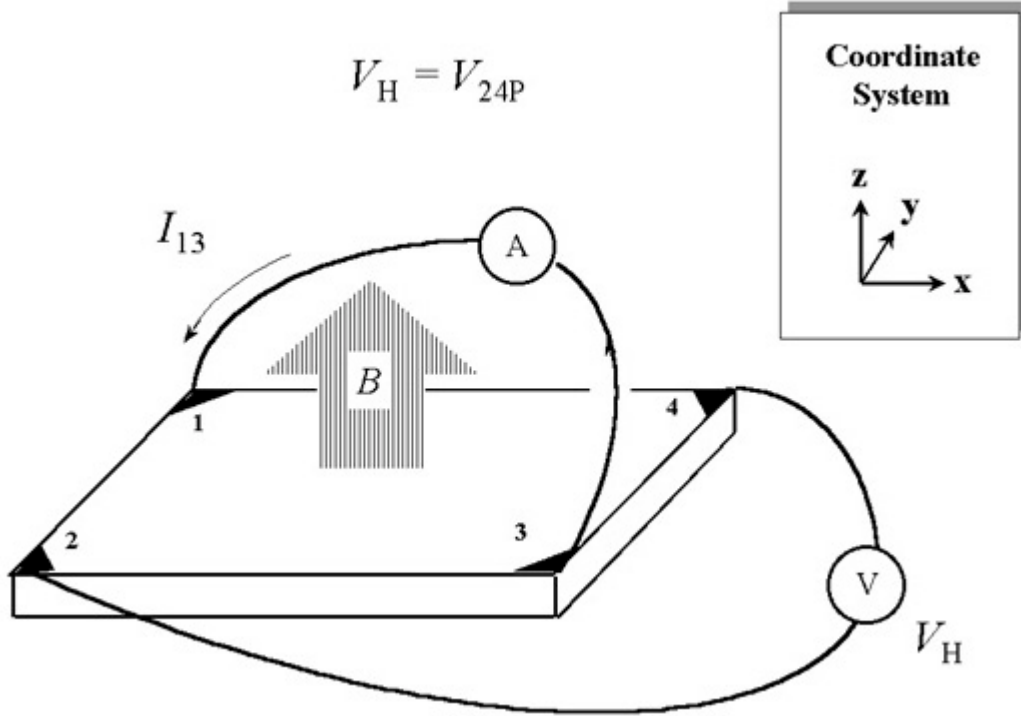


Figure 5: Schematic of a Van der Pauw configuration used in the determination of the Hall voltage V_H .

To measure the Hall voltage V_H , a current I is forced through the opposing pair of contacts 1 and 3 and the Hall voltage $V_H (= V_{24})$ is measured across the remaining pair of contacts 2 and 4. Once the Hall voltage V_H is acquired, the sheet carrier density n_s can be calculated via $n_s = IB/q|V_H|$ from the known values of I , B , and q .

There are practical aspects which must be considered when carrying out Hall and resistivity measurements. Primary concerns are (1) ohmic contact quality and size, (2) sample uniformity and accurate thickness determination, (3) thermomagnetic effects due to nonuniform temperature, and (4) photoconductive and photovoltaic effects which can be minimized by measuring in a dark environment. Also, the sample lateral dimensions must be large compared to the size of the contacts and the sample thickness. Finally, one

must accurately measure sample temperature, magnetic field intensity, electrical current, and voltage.

Sample Geometry

It is preferable to fabricate samples from thin plates of the semiconductor material and to adopt a suitable geometry, as illustrated in Figure 6.

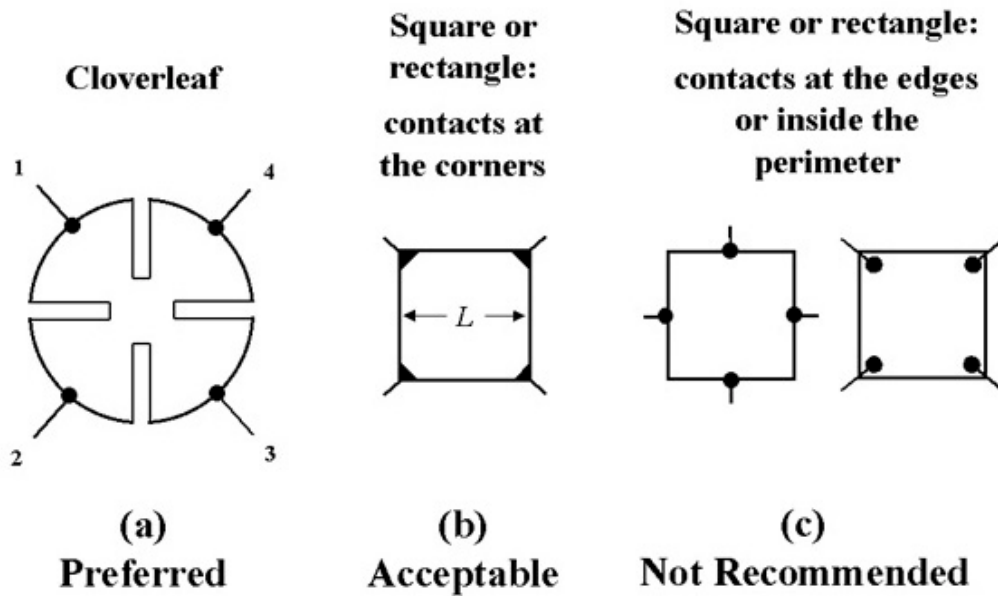


Figure 6: Sample geometries for Van der Pauw resistivity and Hall effect measurements. The cloverleaf design will have the lowest error due to its smaller effective contact size, but it is more difficult to fabricate than a square or rectangle.

The average diameters (D) of the contacts, and sample thickness (d) must be much smaller than the distance between the contacts (L). Relative errors caused by non-zero values of D are of the order of D/L .

The following equipment is required:

- Permanent magnet, or an electromagnet (500 to 5000 gauss)
- Constant-current source with currents ranging from 10 μA to 100 mA (for semi-insulating GaAs, $\rho \sim 10^7 \Omega\cdot\text{cm}$, a range as low as 1 nA is needed)
- High input impedance voltmeter covering 1 μV to 1 V
- Sample temperature-measuring probe (resolution of 0.1 $^\circ\text{C}$ for high accuracy work)

Definitions for Resistivity Measurements

Four leads are connected to the four ohmic contacts on the sample. These are labeled 1, 2, 3, and 4 counterclockwise as shown in Figure 6a. It is important to use the same batch of wire for all four leads in order to minimize thermoelectric effects. Similarly, all four ohmic contacts should consist of the same material.

We define the following parameters (see Figure 4):

ρ = sample resistivity (in $\Omega\cdot\text{cm}$)

d = conducting layer thickness (in cm)

I_{12} = positive dc current I injected into contact 1 and taken out of contact 2.

Likewise for I_{23} , I_{34} , I_{41} , I_{21} , I_{14} , I_{43} , I_{32} (in amperes, A)

V_{12} = dc voltage measured between contacts 1 and 2 ($V_1 - V_2$) without applied magnetic field ($B = 0$). Likewise for V_{23} , V_{34} , V_{41} , V_{21} , V_{14} , V_{43} , V_{32} (in volts, V)

Resistivity Measurements

The data must be checked for internal consistency, for ohmic contact quality, and for sample uniformity.

Set up a dc current I such that when applied to the sample the power dissipation does not exceed 5 mW (preferably 1 mW). This limit can be specified before the automatic measurement sequence is started by measuring the resistance R between any two opposing leads (1 to 3 or 2 to 4) and setting

$$I < (200R)^{-0.5}. \quad (7)$$

- Apply the current I_{21} and measure voltage V_{34}
- Reverse the polarity of the current (I_{12}) and measure V_{43}
- Repeat for the remaining six values (V_{41} , V_{14} , V_{12} , V_{21} , V_{23} , V_{32})

Eight measurements of voltage yield the following eight values of resistance, all of which must be positive:

$$R_{21,34} = V_{34}/I_{21}, R_{12,43} = V_{43}/I_{12}, \quad (8)$$

$$R_{32,41} = V_{41}/I_{32}, R_{23,14} = V_{14}/I_{23}, \quad (9)$$

$$R_{43,12} = V_{12}/I_{43}, R_{34,21} = V_{21}/I_{34}, \quad (10)$$

$$R_{14,23} = V_{23}/I_{14}, R_{41,32} = V_{32}/I_{41}. \quad (11)$$

Note that with this switching arrangement the voltmeter is reading only positive voltages, so the meter must be carefully zeroed.

Because the second half of this sequence of measurements is redundant, it permits important consistency checks on measurement repeatability, ohmic contact quality, and sample uniformity.

- Measurement consistency following current reversal requires that:

$$\begin{aligned} R_{21,34} &= R_{12,43} & R_{43,12} &= R_{34,21} \\ R_{32,41} &= R_{23,14} & R_{14,23} &= R_{41,32} \end{aligned} \quad (12)$$

- The reciprocity theorem requires that:

$$\begin{aligned} R_{21,34} + R_{12,43} &= R_{43,12} + R_{34,21}, \text{ and} \\ R_{32,41} + R_{23,14} &= R_{14,23} + R_{41,32}. \end{aligned} \quad (13)$$

If any of the above fails to be true within 5 % (preferably 3 %), investigate the sources of error.

Resistivity Calculations

The sheet resistance R_S can be determined from the two characteristic resistances

$$\begin{aligned} R_A &= (R_{21,34} + R_{12,43} + R_{43,12} + R_{34,21})/4 \text{ and} \\ R_B &= (R_{32,41} + R_{23,14} + R_{14,23} + R_{41,32})/4 \end{aligned} \quad (14)$$

via the Van der Pauw equation 6. If the conducting layer thickness d is known, the bulk resistivity $\rho = R_S d$ can be calculated from R_S .

Van der Pauw variations:

1. Temperature-dependent Van der Pauw measurements.[5]

This method basically can give profile of electron mobility when impurities have a nonuniform distribution vary with temperature.

2. Differential Van der Pauw measurements.[5]

This method is used to determine the profile of the electron mobility when impurities have a nonuniform distribution vary with depth.

3. Modified Van der Pauw method for microareas.[6]

This method is designed to measure microareas of cross shape.

Two- and Four-Point Probe Method

One of the most common methods of measuring a material's surface resistivity is by using either the two- or four-point probe method.[7] This method uses probes aligned linearly or in a square pattern that contact the surface of the test material.[8] Measuring surface resistivity with four probes dates back to 1916 where Wenner discussed using the technique to measure the earth's resistivity.[7,8] Both two and four probe methods are the most popular methods for measuring resistivity due to the ability of minimizing the parasitic effects of contact resistance, R_c shown below in equation 15.[7,8] To illustrate why four probes are generally used, the two-point probe method is considered for comparison purposes.

In the two point probe method, two voltage probes are at a fixed spacing distance and are moved together along the material surface.[8] Current is sent through one probe and exits through the second probe. The voltage between the two probes is measured by either a potentiometer or a voltmeter.[7] By combining both the voltage and current measurements into the two surface probes, it is possible to calculate material surface resistance between the two probes using the calculation:

$$R_{\text{total}} = \text{Voltage}(V)/\text{Current}(I) = 2R_c + 2R_{\text{sp}} + R_s . \quad (15)$$

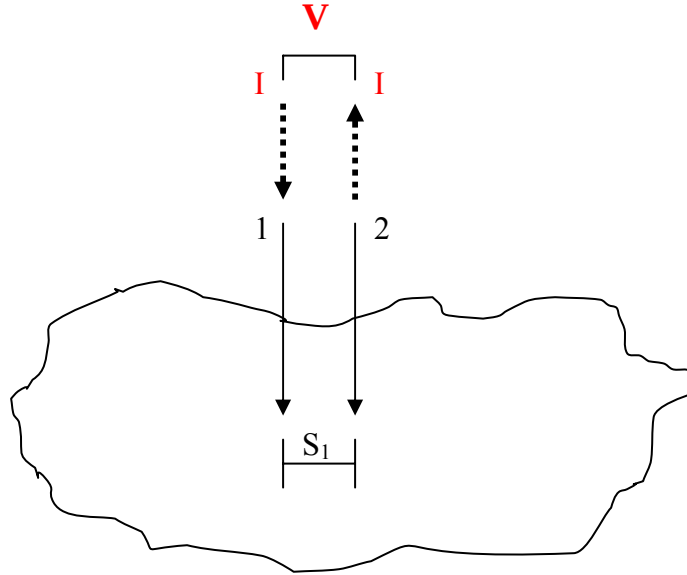


Figure 7: Four point probe test setup. Probes 1 and 4 carry current (I), 2 and 3 measure voltage (V).[7,8,9]

The variable R_c is the parasitic contact resistance made between the material surface and the probe touching the surface. R_{sp} is the spreading resistance, or the parasitic resistance caused by current flowing into the sample surface. The variable of interest is R_s , or the surface resistance of the particular material. Although the two-point probe method is capable of calculating the surface resistivity, the four-point probe method is superior due

to the use of two additional probes. In contrast to the two-point method, the four point method uses the two additional probes to measure the voltage potential of the material surface. These probes do not carry any current, thus eliminating the parasitic resistances R_c and R_{sp} measured in the two-point probe method.

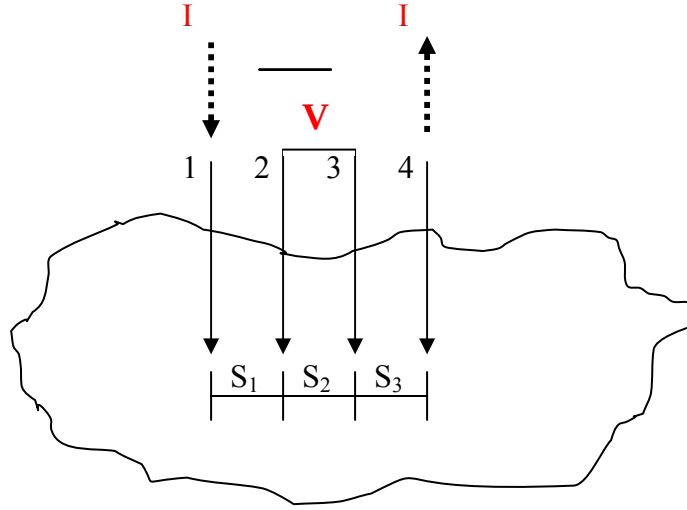


Figure 8: Four point probe test setup. Probes 1 and 4 carry current (I), 2 and 3 measure voltage (V).[7,8,9]

In the four-point probe setup, the voltage potential V adjacent to a probe carrying current can be given by:

$$V = \rho I / 2\pi r \quad (16)$$

Where ρ is the surface resistivity of a material of semi-infinite size, I is the current in the probe, and r is the distance between the voltage measurement and the current probe.[7,8]

Using dimensions in Figure 8, the voltage at probe #2 is,

$$V_2 = \rho I / 2\pi \left\{ (1/S_1) - (1/(S_2 + S_3)) \right\}. \quad (17)$$

The voltage at probe #3 is,

$$V_3 = \rho I / 2\pi \{ (1/(S_1 + S_2)) - (1/S_3) \}. \quad (18)$$

To get total voltage, subtract the voltages $V_2 - V_3$,

$$V = \rho I / 2\pi \{ (1/S_1) + (1/S_3) - (1/(S_2 + S_3)) - (1/(S_1 + S_2)) \}. \quad (19)$$

Rearranging to get the resistivity,

$$\rho = 2\pi V / I / \{ (1/S_1) + (1/S_3) - (1/(S_2 + S_3)) - (1/(S_1 + S_2)) \}. \quad (20)$$

However, if all probe spaces are an equal size s , equation 20 reduces to,

$$\rho = 2\pi s (V/I). \quad (21)$$

Most surface resistivity measurements are made on semiconductor wafers or thin films on a small surface area substrate. Since the measurements are made on finite sized areas, correction factors have to be used based on the sample geometry. This correction factor depends on the sample thickness, edge effects, thickness effects, and the location of the probe on the sample. Many studies have been performed on correction factors, with tables outlining the necessary adjustments. Other considerations that need to be considered for accurate four-point probe measurements are the spacing of the probes, and temperature effects. Small spacing differences in probe spacing can cause the resistivity values to vary widely across a sample surface. A high quality four-point head is necessary to get repeatable and reliable resistivity values. When measuring samples with low resistivity, high currents are needed in the current probes to obtain good voltage readings.

Surface resistivity measurements of Polymeric Films

Why measure surface resistivity of polymeric films?

Polymers, as insulating materials, are used to isolate components of an electrical system from each other and from the ground. For this purpose, it is generally desirable to have the surface resistivity as high as possible. Control of surface resistivity of polymers is of critical importance for the integration of these materials in a wide range of industrial applications such as packaging, conductors, sensors and active electrodes.

Ohm's Law for circuit theory versus Ohm's Law for field theory

As it was mentioned before, ASTM D257 is the standard test method to measure the surface resistivity of insulating materials using the theory of Ohm's law for circuit theory.[1] Unfortunately, Tsai and Bresee showed that the surface resistivity measured by this ASTM method varied by a factor of 2-3 when different circular electrode diameters were used. This happened too when two parallel square electrodes were used at different separation distances.[10]

In this paper, surface resistivity measurements using Ohm's law for circuit theory will be compared with the ones obtained using Ohm's law for field theory. Ohm's law for circuit theory was explained at the beginning of this paper. Ohm's law for circuit theory only provides an approximate way to calculate surface resistivity and may contain substantial errors for high-resistance materials.

When Ohm's law is stated for field theory, surface resistivity is defined as the proportionality constant between the electric field impressed across a homogeneous surface and the current density per unit area flowing in that surface.

$$\epsilon = \rho J \quad (22)$$

Where :

- ϵ = Electric field
- ρ = Resistivity
- J = Current density

Resistivity is the reciprocal of conductivity. Therefore, the same expression could be used in terms of conductivity.

$$\epsilon = 1/\sigma J \quad (23)$$

Where:

- σ = Conductivity

If the electrodes are considered to be two infinite parallel plates as shown in Figure 9, the current density could be expressed as

$$J = \frac{V}{\rho d} \epsilon \quad (24)$$

Where "d" is the distance between the plates

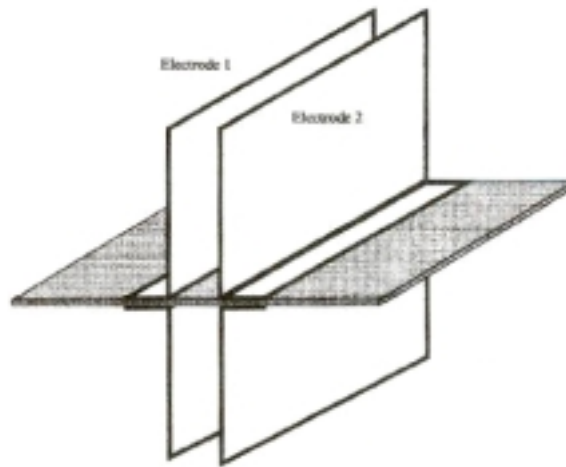


Figure 9: Sample mounted in parallel plate electrodes.

By integrating this expression over the cross-sectional area, the current between the two parallel plates could be obtained.

$$I = \int J \, dA = \frac{V}{\rho d} w$$

Then,

$$\rho = \frac{V}{I} \frac{w}{d}$$

Using the same criteria, the current moving across a sample between two concentric cylindrical electrodes could be derived.

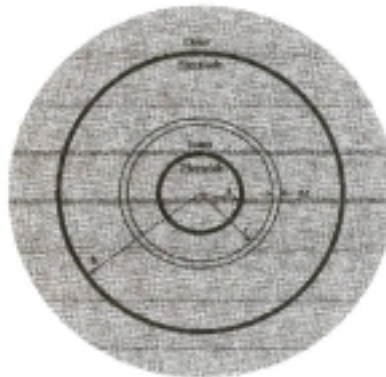


Figure 10: Cylindrical electrode for surface resistivity measurements

In this case, the surface resistivity would be

$$\rho = \frac{2\pi}{\ln(b/a)} \frac{V}{I}$$

Where :

b= diameter of the outer electrode

a = diameter of the inner electrode

Experimental Method

After understanding both Ohm's law theories they must be compared. To perform this comparison three types of electrodes were constructed by Tsai and Bresee.[10]

- **Cylindrical electrodes:** This type electrode is shown in Figure 10. One was constructed with outer diameter of 4.02 cm and the other one with diameter of 6.29 cm. The inner diameter was 0.64 for both of them. This electrode was used to measure the surface resistivity using Ohm's law for field theory
- **Parallel plate electrodes:** This type of electrode is shown in Figure 9. The separation distance for one of them was 2.54 cm and for the other was 5.1 cm. The sample width was 10.2 cm. This electrode was used to measure the surface resistivity using Ohm's law for field theory
- **Square electrode:** This type of electrode is shown in Figure 1. Two solid bars were used with square cross sectional dimensions of 0.32 cm by 0.32 cm. This electrode was used to measure the surface resistivity using Ohm's law for circuit theory.

The material used to measure the surface resistivity using the different electrodes was 3M transparency film, IR 1140. A coaxial wire was connected to one electrode and the voltage supply while the other wire was connected to the other electrode and an ammeter.

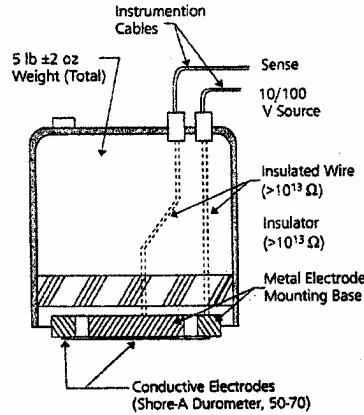


Figure 11: Experimental setup for polymeric film resistivity measurement using cylindrical electrodes.

All this was placed in a stainless steel measurement chamber and covered by another stainless steel plate to form an airtight Faraday cavity to protect the chamber from external electric and magnetic fields. The current density was measured using the three different types of electrodes described before. The results are shown in Table 1 and Table 2.

Table 1: Surface resistivity of IR1140 film measured by Ohm's law for field theory using parallel plate electrodes and cylindrical electrodes.

Electrode Type	Sample Length	Outer electrode Diameter (cm)	Measured Current ($A \times 10^{-12}$)	Surface Resistivity ($\Omega/\text{square} \times 10^{14}$)
Parallel Plate	2.54	n/a	0.308	3.25
Parallel Plate	5.10	n/a	0.155	3.23
Cylindrical	n/a	4.02	1.026	3.32
Cylindrical	n/a	6.29	0.876	3.13

Table 2: Surface resistivity of IR 1140 film measured by Ohm's law for circuit theory using square electrodes.

Electrode Type	Sample Length (cm)	Surface resistivity ($\Omega/\text{square} \times 10^{14}$)
Square	1.0	9.9
Square	2.0	7.2
Square	3.0	6.0

Table 1 shows the resistivity values measured with the parallel plate electrodes were similar even though plate separation distance varied by a factor of 2. If the measurements done with the cylindrical electrode are analyzed it could be said that the values for the resistivity were similar even though outer electrodes diameters differed in a 50%.

Looking at these results it could be concluded that resistivity values based on Ohm's law for field theory are independent of both sample dimension and electrode structure.

On the other hand, Table 2 shows that values of resistivity are not constant when based on Ohm's law for circuit theory. This means that using this theory, resistivity values depend on the length of the test samples. It would be important to mention that the surface resistivity values obtained by Ohm's law for circuit theory did not agree with those obtained using Ohm's law for field theory. It could be concluded that to measure surface resistivity of high resistance polymer films, ASTM test method which is based in Ohm's law for circuit theory is not accurate. Therefore, for this kind of measurements it would be necessary to use Ohm's law for field theory.

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