Four Point Probe Sheet Resistance Measurement

1. What is Sheet Resistance?

Sheet resistance (also known as **surface resistance** or **surface resistivity**) is a common electrical property used to characterize thin films of conducting and semiconducting materials. It is a measure of the lateral resistance through a thin square of material, i.e. *the resistance between opposite sides of a square*. The key advantage of sheet resistance over other resistance measurements is that it is independent of the size of the square - enabling an easy comparison between different samples. Another advantage is that it can be measured directly using a four-point probe.

Sheet resistance (**R_S**) is commonly defined as the resistivity (**ρ**) of a material divided by its thickness (**t**):

$$R_S = \frac{\rho}{t}$$

The units of this equation resolve to ohms (Ω); however, it actually represents the resistance between opposite sides of a square of a material (rather than bulk resistance). As such the units Ω/□ (ohms per square) are commonly used.

1.1 Examples of Applications

Sheet resistance is a critical property for any thin film of material in which electrical charges are intended to travel along (rather than pass through). For example, thin-film devices (such as perovskite solar cells or organic LEDs) require conducting electrodes which generally have thicknesses in the nanometer to micrometer range. Figure 1 shows how charges move within an LED device. The electrodes must transport electrical charge laterally and need low sheet resistances to reduce losses during this process. This becomes even more important when attempting to scale up the size of these devices, as the electrical charges will have to travel further along the electrodes before they can be extracted.

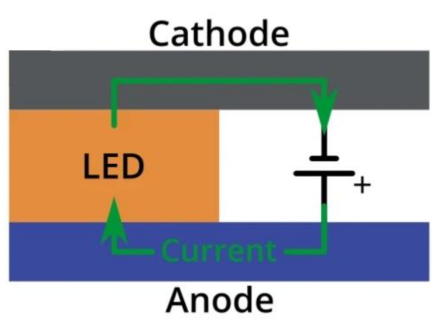

Figure 1.0: A schematic diagram of a thin film LED, showing current flowing laterally through the electrodes to the active material. The sheet resistance of the electrodes will affect amount of current that reaches the LED, impacting its performance.

Furthermore, the resistivity and conductivity can be calculated if the sheet resistance and material thickness are known. This allows for the materials to be electrically characterized, purely by measuring their sheet resistance.

1.2 Measuring Sheet Resistance

The primary technique for measuring sheet resistance is the four-probe method (also known as the **Kelvin technique**), which is performed using a four-point probe. A **four-point probe** consists of four electrical probes in a line, with equal spacing between each of the probes as shown in Figure 2.

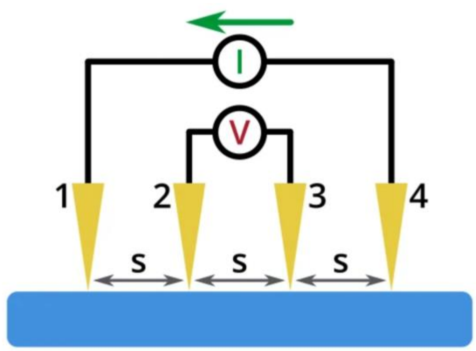

Figure 1.1: A schematic diagram of a four-point probe. The four probes have equal spacing (**s**) and are shown in contact with a surface. A current (**I**) is injected through probe 1 and collected through probe 4, whilst the voltage is measured between probes 2 and 3.

It operates by applying a current (**I**) on the outer two probes and measuring the resultant voltage drop between the inner two probes. The sheet resistance can then be calculated using the equation below:

$$\mathrm{R_S} = \frac{\pi}{\ln(2)}\frac{\Delta V}{I} = 4.53236\frac{\Delta V}{I}$$

It should be noted that this equation is only valid if:

i) The material being tested is no thicker than 40% of the spacing between the probes, and
ii) The lateral size of the sample is sufficiently large. If this is not the case, then geometric correction factors are needed to account for the size, shape, and thickness of the sample. The value of this factor is dependent on the geometry being used, and is covered in detail in the next section.

1.3 Geometric Correction Factors

Whilst the above equation for sheet resistance is independent of sample geometry, this only applies when the sample is significantly larger (typically having dimensions 40 times greater) than the spacing of the probes, and if the sample is thinner than 40% of the probe spacing. If this is not the case, the possible current paths between the probes are limited by the proximity to the edges of the sample, resulting in an overestimation of the sheet resistance. To account for this difference, a correction factor based upon the geometry of the sample is required.

1.3.1 Circular Samples

For a circular sample of diameter **d**, measured at the center of the sample, the correction factor can be calculated using:

$$C = \frac{\ln(2)}{\ln(2) + \ln\left({d^2}/{s^2} + 3\right) - \ln({d^2}/{s^2} - 3)}$$

Where **d** is the distance between probes. When **d >>s** this equation tends to unity, enabling the use of the uncorrected equation.

1.3.2 Rectangular Samples

For a rectangular sample, the determination of the geometrical correction factor is slightly more complicated as there is no equation. Instead, a table of empirically-determined correction factors is used. The values in this table only apply when the probes make contact in the center of the sample, and are aligned parallel to the sample's longest edge (**l**), as shown in Figure 1.2.

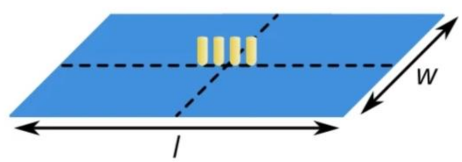

Figure 1.2: Illustration of probe positioning and dimensions for a rectangular sample with **l ≥ w**.

As an example, suppose the rectangular sample shown in the figure above has a long edge of **l** = 20 mm and short edge of **w** = 10 mm, and the spacing of the probes being used is **s** = 2 mm. In this case, **l** / **w** = 2 and **w** / **s** = 5, so the table is searched for the correction factor which satisfies these two values, looking along the columns for **l** / **w** = 2 and the rows for **w** / **s** = 5, which is **C** = 0.7887. The measured sheet resistance is multiplied by this value to get the correct value for the sample.

w / s	l / w = 1	l / w = 2	l / w = 3	l / w = 4
1			0.2204	0.2205
1.25			0.2751	0.2751
1.5		0.3263	0.3286	0.3286
1.75		0.3794	0.3803	0.3803
2		0.4292	0.4297	0.4297
2.5		0.5192	0.5194	0.5194
3	0.5422	0.5957	0.5958	0.5958

4	0.6870	0.7115	0.7115	0.7115
5	0.7744	0.7887	0.7887	0.7887
7.5	0.8846	0.8905	0.8905	0.8905
10	0.9313	0.9345	0.9345	0.9345
15	0.9682	0.9696	0.9696	0.9696
20	0.9822	0.9830	0.9830	0.9830
40	0.9955	0.9957	0.9957	0.9957
∞	1	1	1	1

Table 1.1: Table of rectangular shapes correction factors

Obviously, not every sample will fall neatly into these categories. If this is the case, it is recommended that cubic spline interpolation is used to estimate the appropriate correction factor for the sample.

It is important to note that the correction factors for circular and rectangular samples detailed above only apply for measurements taken in the *center of the sample*. If the measurement is not in the center, different correction factors are needed.

1.3.3 Other Shapes and Probe Positions

For different sample shapes and for measurements not performed at the center of the sample, alternative correction factors are required. Most of these can be found in Haldor Topsøe, *Geometric Factors in Four Point Resistivity Measurement* , 1966, or F. M. Smits, *Measurement of Sheet Resistivity with the Four-Point Probe* , Bell Syst. Tech. J., May 1958, p. 711.

If the shape of the sample is irregular, consider whether it is closer to rectangular or circular and then estimate what size of that shape could fit within the sample.

1.3.4 Thick Samples

If the sample being tested is thicker than 40% of the probe spacing, an additional correction factor is required. The correction factor used is dependent upon the ratio of the sample thickness (t) to the probe spacing (s) and some of the possible values are listed in the table below:

t / s	Correction Factor
0.4	0.9995
0.5	0.9974
0.5555	0.9948
0.6250	0.9898
0.7143	0.9798
0.8333	0.9600

1.0	0.9214
1.1111	0.8907
1.25	0.8490
1.4286	0.7938
1.6666	0.7225
2.0	0.6336

Table 1.2: Table of thickness correction factors

As with the rectangular samples, if **t/s** does not equal one of the values given in the table, a cubic spline interpolation is recommended to estimate the appropriate correction factor for the sample.

1.4 Four Point Probe Equation Derivation

In order to determine how the sheet resistance of a thin film is measured using a four-point probe, a simplified scenario must first be evaluated. Imagine an arbitrarily sharp probe contacting and injecting current (through an applied voltage) into a semi-infinite volume (infinite in all directions except towards the probe) of a conductive material.

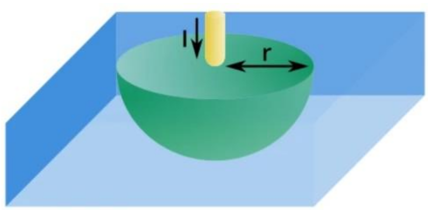

Figure 1.3: A probe injecting current I into a semi-infinite volume of conductive material. The green hemisphere is a shell of the injected current with radius **r**.

The current travels outwards from the point of contact through concentric hemispherical shells of equipotential, each of which has current density (**J**) of:

$$J = \frac{I}{2\pi r^2}$$

Where **r** is the radial distance from the probe ($2\pi r^2$ being the surface area of the hemisphere). By applying Ohm's Law (**E = ρJ**) with the electric field across each shell equal to the voltage drop over the shell thickness, or **-ΔV / Δr** (this term is negative as voltage decreases with **r**), and with the thickness of the shell tending towards zero, the following equation is obtained:

$$\frac{dV}{dr} = -\rho\left(\frac{I}{2\pi r^2}\right)$$

This can be integrated between **r** and **r'** to obtain:

$$V - V' = \frac{\rho I}{2\pi}(\frac{1}{r} - \frac{1}{r'})$$

By applying the boundary condition that **V** approaches zero as **r** approaches infinity, the equation simplifies to:

$$V = \frac{\rho I}{2\pi}$$

Now imagine that there are four arbitrarily sharp probes (labeled 1 to 4) in contact with the semi-infinite conducting material, which are in a line with equal spacing (**s**). They are set up so that current is injected through probe 1 and collected by probe 4 as shown in Figure 1.1. If equivalent boundary conditions are assumed for each probe, the voltage at any point is equal to the sum of the voltage due to each probe separately, i.e.:

$$V = \frac{\rho I}{2\pi}(\frac{1}{r_1} - \frac{1}{r_4})$$

Where **r1** and **r4** are the radial distances from probe 1 and probe 4 respectively. Measurements of the voltage are then made between probes 2 and 3. Using the above equation, the voltage at probes 2 and 3 are:

$$V_2 = \frac{\rho I}{2\pi}(\frac{1}{s} - \frac{1}{2s})$$

$$V_3 = \frac{\rho I}{2\pi}(\frac{1}{2s} - \frac{1}{s})$$

Hence, the change in voltage (**ΔV**) between probes 2 and 3 is:

$$\Delta V = V_2 - V_3 = \frac{\rho I}{2\pi}\left(\frac{2}{s} - \frac{1}{s}\right) = \frac{\rho I}{2\pi s}$$

Therefore, the resistivity between the probes is:

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

This expression only applies in the case of a semi-infinite volume, and does not apply in the case of a thin film. However, a new expression can be derived using a similar analysis. As before, imagine the arbitrarily sharp probe contacting and injecting current into a thin film of material with thickness **t**.

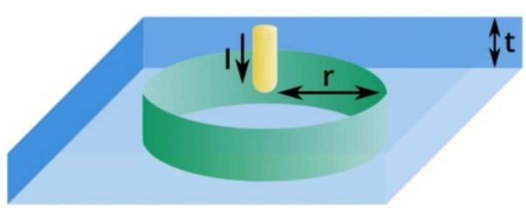

Figure 1.4: A probe injecting current **I** into a thin film of conductive material with thickness **t**. The green cylinder is a shell of the injected current with radius **r**.

In this case, the current travels away from the probe (through the material) in short cylindrical shells of equipotential, each with a current density of:

$$J = \frac{I}{2\pi rt}$$

By applying the same conditions for the electric field as previously (Ohm's Law and shell thickness tending to zero), the electric field across each shell is:

$$\frac{dV}{dr} = -\rho(\frac{I}{2\pi rt})$$

The resistivity has already been defined as the sheet resistance multiplied by the thickness of the materials, so this can be replaced in the above equation to give:

$$\frac{dV}{dr} = -\mathrm{R}_s(\frac{I}{2\pi r})$$

This can be integrated between **r** and **r'** to obtain:

$$V - V' = \frac{IR_s}{2\pi}\left(ln\frac{1}{r} - ln\frac{1}{r'}\right) = \frac{IR_s}{2\pi}(ln\, r' - \ln\, r)$$

Unlike before, it cannot be assumed that the voltage tends to zero as r approaches infinity as the natural logarithm of infinity is not zero. However, this does not impact the analysis as the difference in voltage at different points (**ΔV**) is the value measured by the four-point probe.

Now imagine the four-probe system in contact with a thin film, with an additional condition that the thickness of the film (**t**) is negligible compared to the probe spacing (**s**). For current being injected by probe 1 and collected by probe 4, the equation becomes:

$$V = \frac{IR_s}{2\pi}(lnr_4 - lnr_1)$$

The voltages measured at probes 2 and 3 are therefore:

$$V_2 = \frac{IR_s}{2\pi}(ln2s - lns)$$

$$V_3 = \frac{IR_s}{2\pi}(lns - ln2s)$$

Hence, the change in voltage is:

$$\Delta V = V_2 - V_3 = \frac{IR_s}{2\pi}(2ln2s - 2lns) = \frac{IR_s}{\pi}ln2$$

This can be rearranged to give:

$$\mathrm{R_S} = \frac{\pi}{\ln(2)} \frac{\Delta V}{I} = 4.53236 \frac{\Delta V}{I}$$

Therefore, by measuring the change in voltage between the inner probes and the applied current between the outer probes, we can measure the sheet resistance of a sample.

For this manual we will use Ossila Four Point Probe System for Sheet Resistivity Measurement.

2 Ossila Four Point Probe System

2.2 Overview

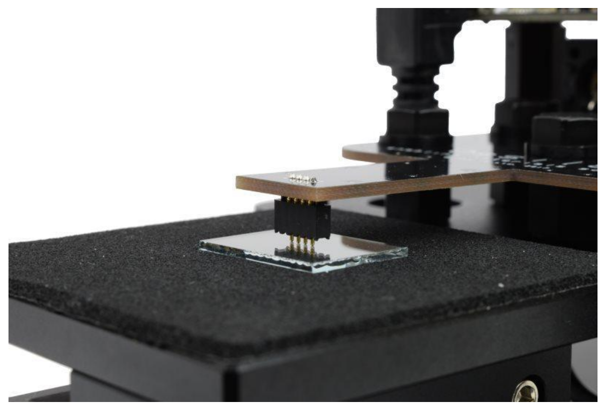

Figure 2.0: Ossila Four Point Probe System

Ossila Four Point Probe System includes a four-point probe, source measure unit and easy to use PC software – enabling more laboratories to measure sheet resistance for affordable price. The probe head uses gentle spring – loaded contacts instead of sharp needles, minimizing damage to delicate samples (e.g. polymer films that are only a few nanometers thick).

The system is operated via the specifically – designed PC software, which automatically calculates appropriate geometrical correction factors for the sample to give accurate values for the sheet resistance. If the sample thickness is provided, the software will further calculate resistivity and conductivity.

2.3 Safety

2.3.1 Warning

Absolute maximum input voltage is ±12 volt. DO NOT apply input while not powered.

2.3.2 Use of equipment

The Ossila Four Point Probe System is designed to be used as instructed. It is intended for use under the following conditions:

- Indoors in laboratory environment (Pollution Degree 2)
- Altitudes up to 2000m
- Temperatures of 5°C to 40°C; maximum relative humidity of 80% up to 31°C

The unit supplied with a 24 V/2A power adapter with power cord for the country of purchase, in accordance with European commission regulations and British standards. *Use of any other electrical power cables, adaptors or transformers is not recommended.*

2.4 Requirements

Power	24V/ 2A DC (supplied with the system)
Operating system	Windows Vista,7,8 or 10(32-bit or 64 bit)
CPU	Dual Core 2 GHz
RAM	2 GB
Available Hard Drive space	178 MB
Monitor Resolution	1440 × 900
Connectivity	USB 2.0 or newer, or Ethernet (requires DHCP)

Table 2.0: Four Point Probe System and Ossila Sheet resistance software requirements.

2.5 Unpacking

The standard items included with the Ossila Four Point Probe System are:

- The Ossila Four Point Probe System
- 24V/2A power adaptor with a cord set specifically for country of operation (UK,USA,EU or AU)
- USB-B cable
- USB memory stick pre-loaded with the user manual, USB drivers, QC data, and software installer
- Printed copy of the user manual
- 100nm ITO coated glass substrate (20×15 mm)

2.6 Specifications

Voltage range	±100µV to ±10V
Current range	±10nA to ±150mA
Sheet resistance range	3mΩ/square to 10MΩ/square
Measurement accuracy	<±4%
Measurement precision	±0.5%
Probe spacing	1.27 mm
Rectangular sample size range	Long edge minimum: 4mm Short edge maximum: 60mm

Circular sample size range	4 mm to 76.2 mm
Maximum sample thickness	10 mm
Overall dimensions	Width: 145 mm Height: 150 mm Depth: 240 mm

Table 2.1: Four Point Probe System measurement specifications.

2.7 Installation

1. Install the Ossila Sheet Resistance software on your PC
   I. Run the 'Ossila-Sheet-Resistance-Installer-vX-X-X-X.exe' on the USB memory stick provided.

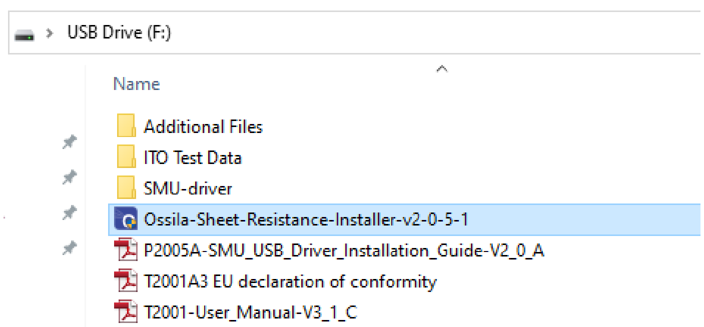

Figure 2.1: The Ossila-Sheet-Resistance-Installer on the USB.

   II. Follow the on screen instructions to install the software.
      - Run the Ossila-Sheet-Resistance-Installer .exe file and press 'Next'.

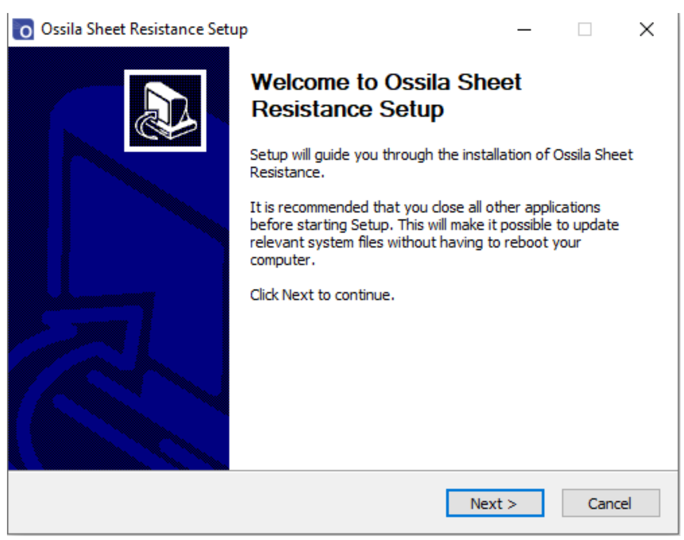

Figure 2.2: Running the Ossila Sheet Resistance Setup.

      - Press 'Install', then it will extract and install the files automatically.

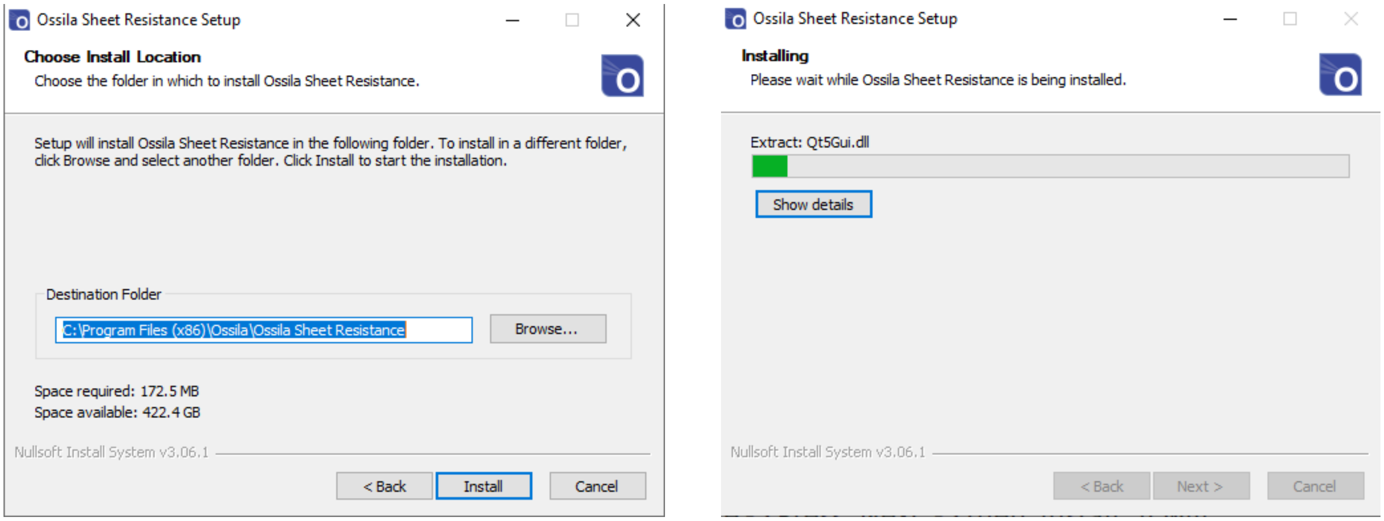

Figure 2.3: Installing Ossila Sheet Resistance Setup.

- Finally press 'Finish'' on the upcoming wizard box then launch the software.

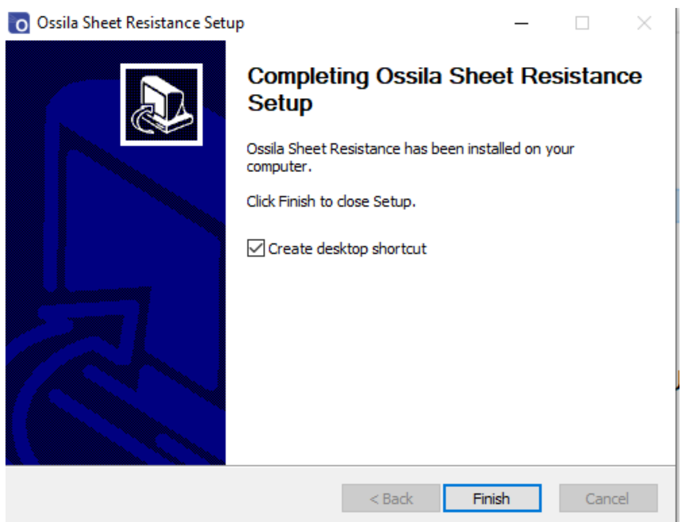

Figure 2.4: Completing Ossila Sheet Resistance Setup

2. Install the Source Measure Unit USB drivers on your pc.

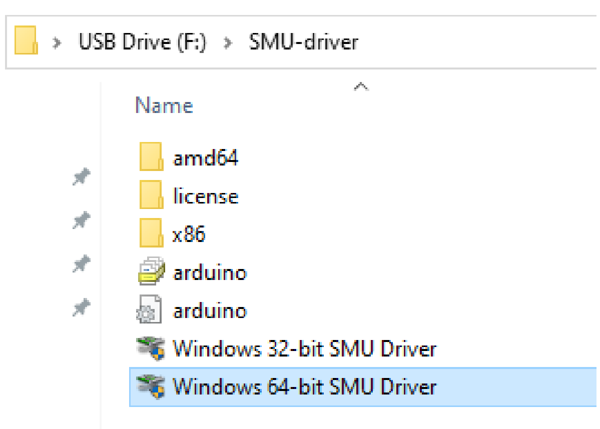

Figure 2.5: The SMU Driver on the USB.

I. On the USB memory stick provided, open the 'SMU-Driver' folder and run either 'Windows 32-bit SMU Driver' for 32-bit operating system or 'Windows 64-bit SMU Driver' for 64-bit operating systems.
II. Note that, on Windows 10, the driver will install automatically when the unit is connected.
III. If the drivers fail to install, please refer to the SMU USB Driver installation Guide found on the USB memory stick.

3. Connect the 24V DC power adapter to the power socket on the rear of the unit.
4. Connect the unit to your PC using the provided USB-B cable or an Ethernet cable if preferred.
    I. If you are using a USB connection and the unit is not detected, please refer to the SMU USB Driver installation Guide found on the USB memory stick.

2.8 Operation

2.8.1 Taking measurements

1. Place your sample in the center of the vertical stage.
2. Raise the platform until the probes have retracted approximately half-way into their housing.
    I. One full turn of the micrometer (after initial contact is made) is a good way to ensure that there is good electrical contact between the probes and your sample.
    II. Ensure that the probes make contact with the center of the sample.
    III. For rectangular samples, the longest edge should be aligned parallel to the probes.
3. Start the Ossila Sheet Resistance software. The window shown in figure 2.5 will open.

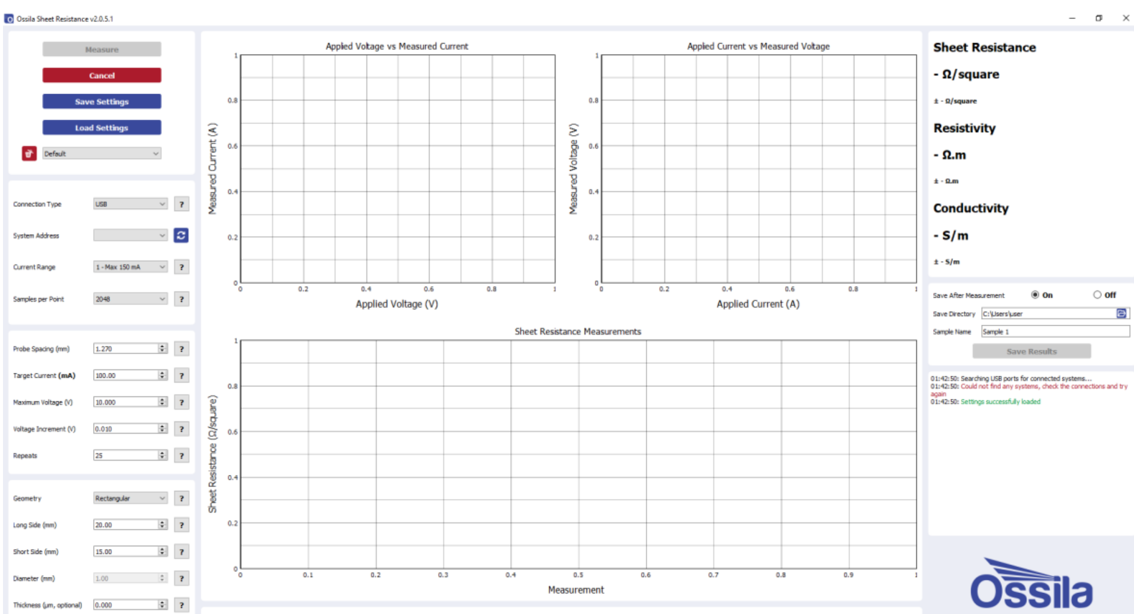

Figure 2.6: Ossila Sheet Resistance software.

4. Set the appropriate settings in the software (explained in more detail in section 2.7.2).
5. Click the 'Measure' button.

I. The unit will apply a voltage and measure the current across the sample.
II. The voltage will be increased until either the target current is achieved, or the maximum voltage is reached.

- If the maximum voltage is reached before the target current is achieved the measurement will cancel.

III. If the target current is achieved, the **sheet resistance** will then be measured.
IV. The measurement will be repeated for the number of times set in the 'Repeats' field, and the average will be displayed on the right.

- These measurements will use the applied voltage found in the initial sweep to supply the current.

V. If a thickness has been provided, the average **resistivity** and **conductivity** will also be displayed.

Here the sheet resistance will be measured in the unit of **Ω/square, r**esistivity **Ω.m** and conductivity, **S/m** (siemen/meter).

> Note: $\rho = R\frac{A}{l}$ has unit of Ω.m
>
> And we know that $\sigma = \frac{1}{\rho}$ has unit of $\frac{1}{\Omega.m}$ from this 1/Ω is called **siemen (S).** Then unit of conductivity becomes S/m.

6. If automatic saving is turned on, the measurement data and setting will then be saved.

2.9 Software settings

There are several settings in the program which must be filled in before taking a measurement. These are found in the column on the left of the window as shown in figure 2.6

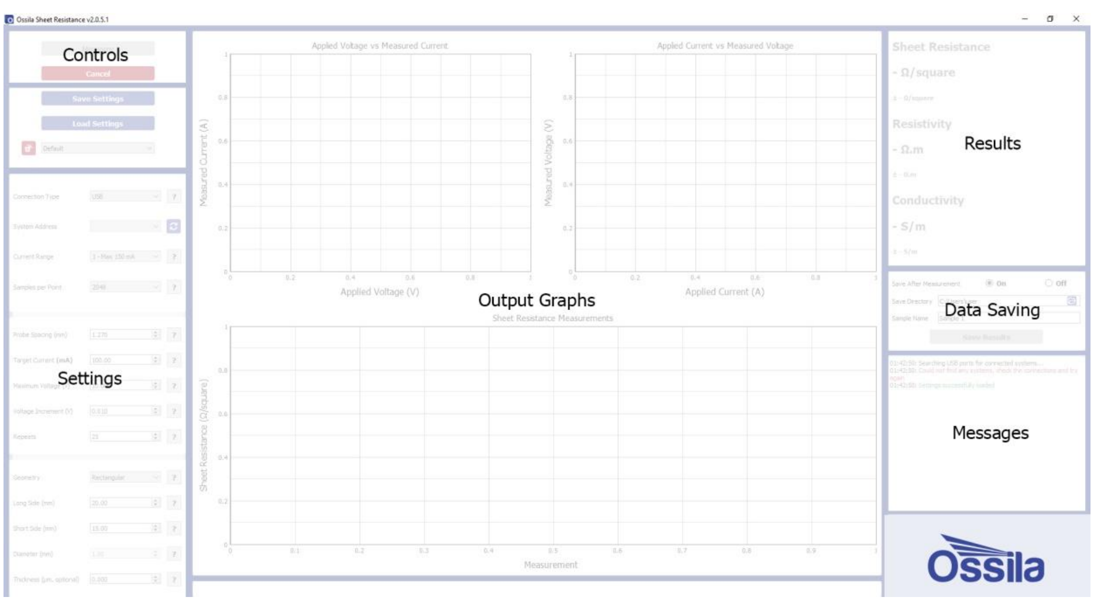

Figure 2.7: Layout of the Ossila Sheet Resistance software window.

2.9.1 Connection

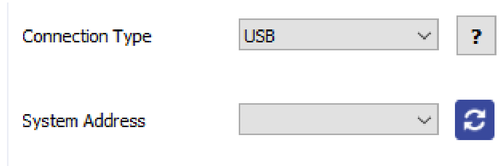

Figure 2.8: Connection setting.

I. Connection Type

- Select the type of connection you are using either USB or Ethernet.
    - I. Any connected units will be automatically detected when a selection is made and the 'System Address' box will be populated.
- The software will search for units connected via USB on start up.
    - I. To rescan for connected units (in case the connection is changed) click the refresh icon next to the system 'system Address' box.

II. System Address

- Select the COM port or IP address of the connected unit you intend to use (USB and Ethernet connection respectively).
    - I. This box will be populated automatically with the addresses of any units connected to the computer via the method selected in the 'connection Type' box.

2.8.2 System Setting

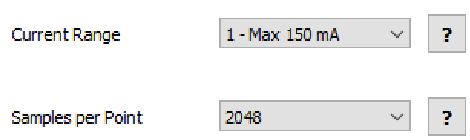

Figure 2.9: System setting.

I. Range

- Select the range of currents to be used for the measurement.
    - I. This defines the upper limit and accuracy of current measurements that can be performed by the unit. The values for each range given in table 2.2.
    - II. The maximum current values for each range are also shown in the range selection box.

Range	Maximum current	Accuracy
1	150 mA	±200 µA
2	20 mA	±10 µA
3	2000 µA	±1 µA
4	200 µA	±100 nA
5	20 µA	±10 nA

Table 2.2: maximum current and accuracy for the different range settings for the Four-Point Probe System.

II. Samples per point

- Select the number of samples to be taken for each measurement.
    I. A higher number of samples per point will improve the accuracy and precision of the measurement. However, this will increase the time taken for it to be performed.

2.8.3 Experimental Parameters

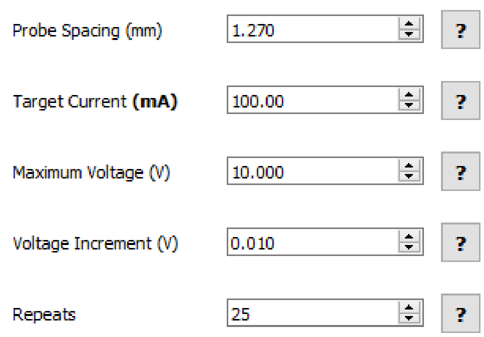

Figure 2.10: Experimental parameters settings.

I. Probe Spacing

- Sets the spacing between each of the probes in mm.
    I. This is required to determine the appropriate geometric correction factor for the sample being measured.

II. Target Current

- Sets the current to apply to the sample for the measurement.
- The units and maximum values of this field will be dependent upon the selected Range.
- This value can be positive or negative.
- The value that should be used for this field is dependent upon the resistance of the sample being tested.
    I. Higher values for less resistive samples.
    II. Lower values for more resistive samples.

III. Maximum Voltage

- Sets the maximum voltage that can be applied to the sample to achieve the target current.
    I. 10V is the maximum that can be set.
    II. The polarity of the voltage will be set automatically, based upon the target current.

IV. Voltage Increment

- Sets the step size for increasing/ decreasing the voltage when trying to achieve the target current.

V. Repeats

- Sets the number of measurements that will be taken to generate an average for the results.

2.8.4 Sample Details

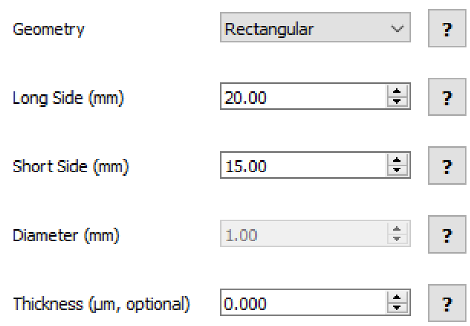

Figure 2.11: Sample details settings.

I. Geometry

- Select the geometry of the sample being measured
  - I. This is required to calculate the geometrical correction factor for the current sample.
  - II. If the shape of the sample is irregular, consider whether it is closer to rectangular or circular and then estimate what size of that shape could fit within the sample.

II. Long side (Rectangular Sample)

- Sets the length of the long side of the sample in mm (if the sample is rectangular)
  - I. This is required for calculating the appropriate geometrical correction factor.

III. Short side (Rectangular Sample)

- Sets the length of the short side of the sample in mm (if the sample is rectangular)
  - II. This is required for calculating the appropriate geometrical correction factor.

IV. Diameter (Circular Sample)

- Sets the diameter of the sample in mm (if the sample is circular)
  - III. This is required for calculating the appropriate geometrical correction factor.

V. Thickness (Optional)

- Sets the thickness of the sample in μm.
  - I. This enables the calculation of the resistivity and conductivity of the sample.
  - II. It is not needed for sheet resistance measurements, thus can be set to 0 if not known.

2.8.5 Saving and loading settings

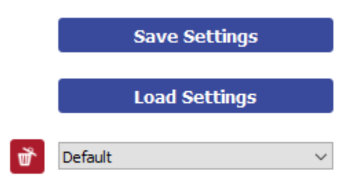

Figure 2.12: Controls for saving and loading settings profiles.

I. Save settings

- Saves the current setting as a profile that can be loaded quickly for use at another time.
- When clicked, you will be promoted to name the setting profile.

    I. If the name is already in use, you will be asked if you wish overwrite the previous profile.
    II. The name cannot contain the characters: \ /:*?’’<>|
    III. You can change the default setting by choosing the name ‘Default’.
- The setting profile will be added to the drop down box using the given name.

II. Load settings

- Opens a dialog box to navigate to a setting file that has been created as part of a previous measurement.
    I. The settings fields will be populated with the values in the setting file.

III. Settings profiles

- Select a saved setting profile from the drop down box.
    I. The setting fields will be populated with the saved values.
- Settings profile can be deleted by selecting the profile and then clicking the red ‘Delete ’ icon next to the drop down box.

2.8.6 Saving Results

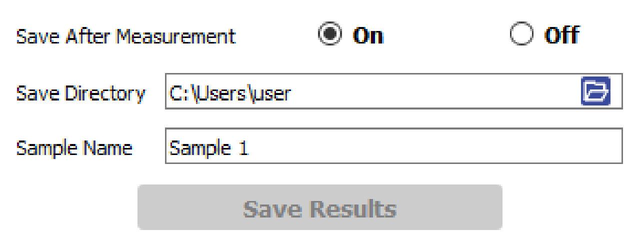

Figure 2.13: Save settings pane.

I. Automatic saving

- The program allows for data to be saved automatically, as well as manually once the measurement is complete.
    I. To enable or disable automatic saving choose the appropriate option from the drop down box.
    II. For automatic saving, the ‘Save Directory’ and ‘Sample name’ fields must be filled in before the measurement can start, these are detailed below.

II. Save Directory

- Sets the location in which to save the results.
- This can be set either by:
    I. Manually typing the directory into the field.
    II. Copying and pasting it from your file explorer.
    III. Clicking the ‘Select Directory’ button, this will open a dialog box to allow the selection of a folder to save to.

III. Experiment Name

  - Sets the name of the folder in which the files will be saved.

I. The name cannot contain the characters: \ /:*?”<>|

IV. **Save Results**

- Clicking this button will manually save the measurement results.

V. Saved Data Format

- When saving a folder with the chosen experiment name will be created in then specified directory and populated with 3 .csv (comma separated values) files:
  I. The data for the initial current-voltage sweep.
  II. The sheet resistance measurements.
  III. The settings of the experiment (this file can be loaded by the program if you wish to use the same setting again).

2.8.7 Controls

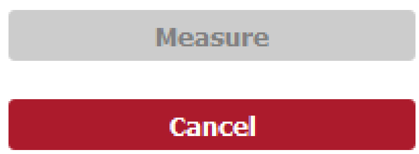

Figure 2.14: Controls of the Ossila Sheet Resistance software.

I. Measure

- Clicking this button will start the measurement using the chosen settings.
- This button cannot be clicked if the software has not detected a unit.

II. Cancel

- Stops a measurement that is currently in progress.
  I. Note that if the measurement is stopped before it completes, the user will be unable to save the experimental data.

3 Investigating sheet resistivity of ITO (indium tin oxide)

The sample provided for this experiment has a thickness of 100 nm and its size is 15×20 mm with rectangular shape. Here we will investigate the effect of parameters on sheet resistivity, resistance and conductivity by varying their value.

3.2 Probe Spacing

The default probe spacing value is set to 1.270 mm. Let us measure the sheet resistivity of the ITO setting the thickness 100nm (0.1µm) and leaving other parameters unchanged or as default.
The results are shown in figure 3.0 below:

- Sheet resistance = 16.3 Ω/square
- Resistivity = 1.63 µΩ.m
- Conductivity = 613.6 kS/m

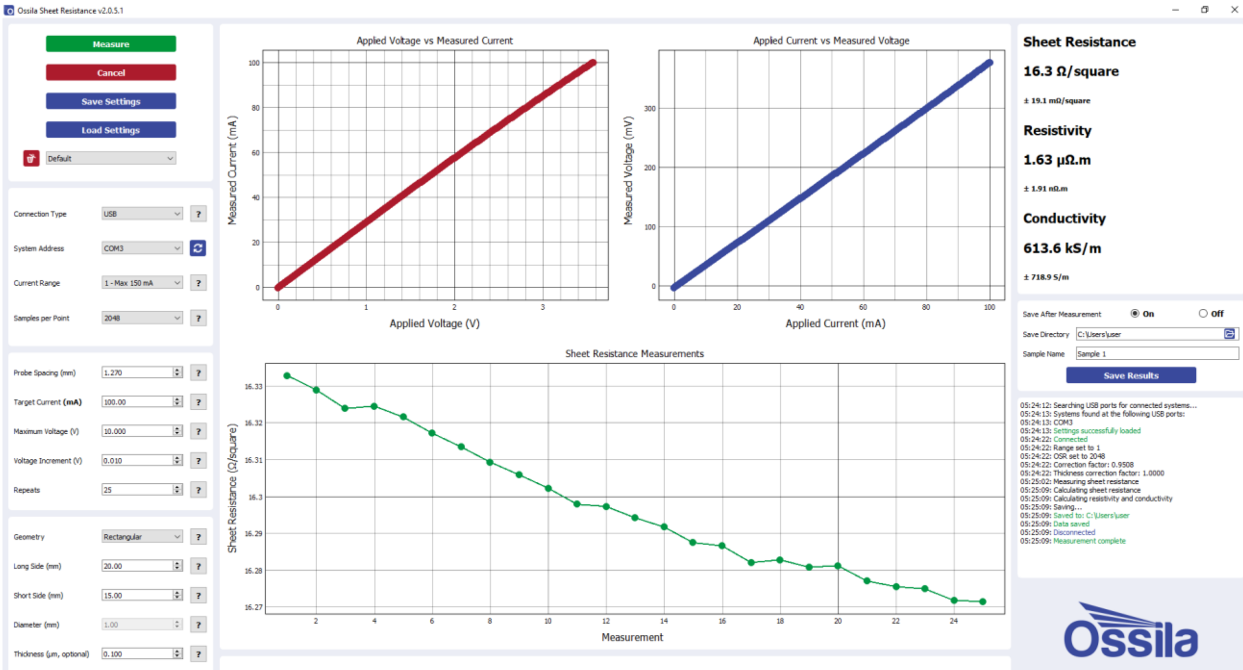

Figure 3.0: Sheet resistivity of ITO at 1.270mm probe spacing.

Now, let us increase the probe spacing to 1.500 mm and measure the sheet resistivity of ITO without changing other parameters.

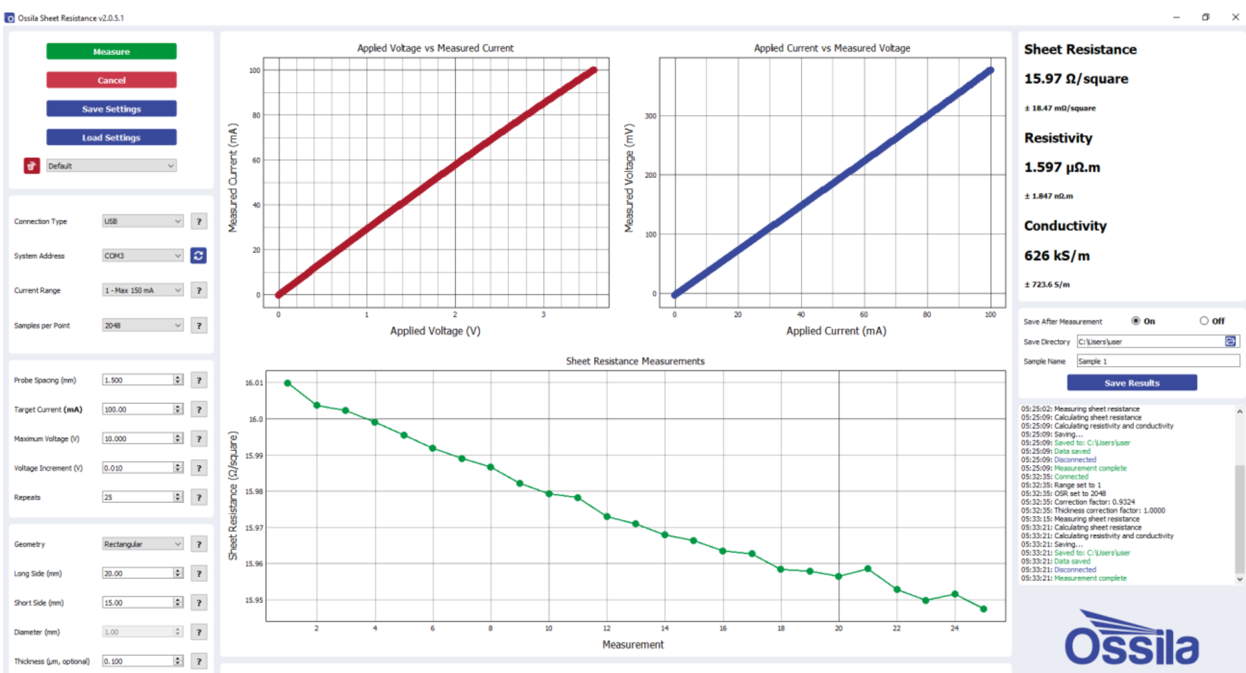

Figure 3.1: Sheet resistivity of ITO at 1.500mm probe spacing.

The results shown in figure 3.1 above are:

- Sheet resistance = 15.97 Ω/square
- Resistivity = 1.597 μΩ.m
- Conductivity = 626 kS/m

Now, let us decrease the probe spacing to 0.9mm and measure the sheet resistivity of ITO without changing other parameters.

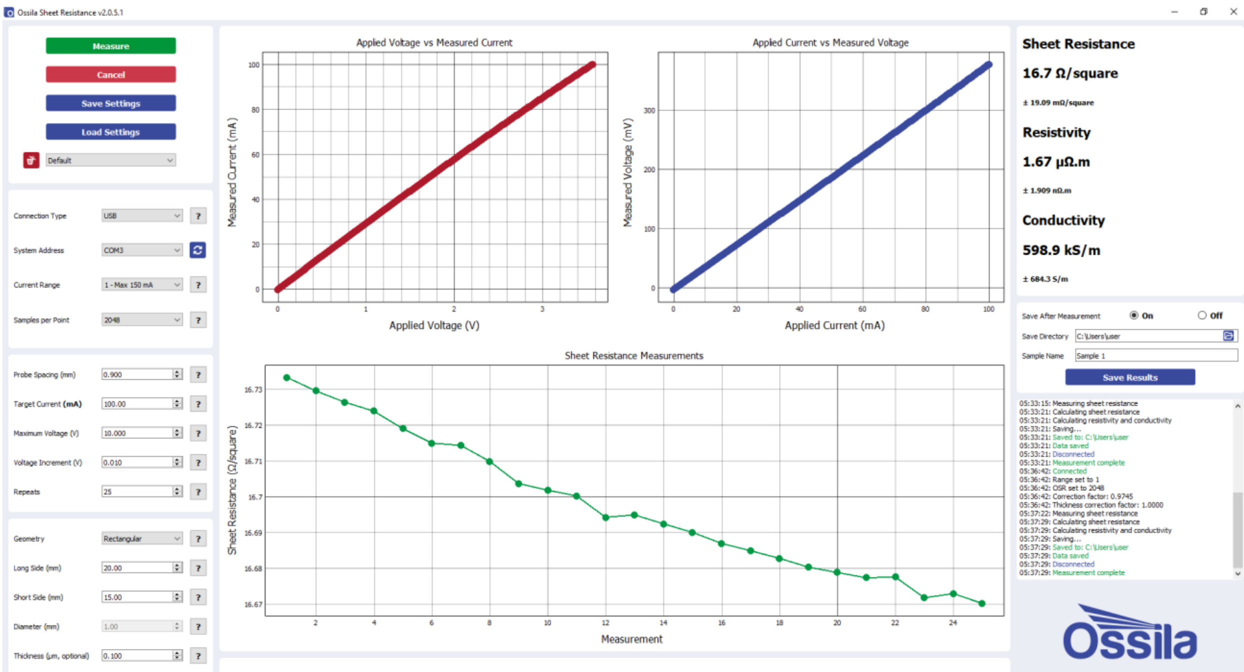

Figure 3.2: Sheet resistivity of ITO at 0.9mm probe spacing.

The results shown in figure 3.2 above are:

- Sheet resistance = 16.7 Ω/square
- Resistivity = 1.67 μΩ.m
- Conductivity = 598.9 kS/m

Questions

1. What do you observe? Does the probe spacing affect the sheet resistivity of ITO?

3.3 Current Range and Target Current

The default current range is 1 – Max 150 mA and target current 100mA. Let us measure the sheet resistivity of the ITO setting the thickness 100nm (0.1μm) and leaving other parameters unchanged or as default. This would have the same result as figure 3.0 which are:

- Sheet resistance = 16.3 Ω/square
- Resistivity = 1.63 μΩ.m
- Conductivity = 613.6 kS/m

Now, let us increase the target current to 140mA and measure the sheet resistivity of ITO without changing the current range (1 – Max 150 mA) and other parameters.

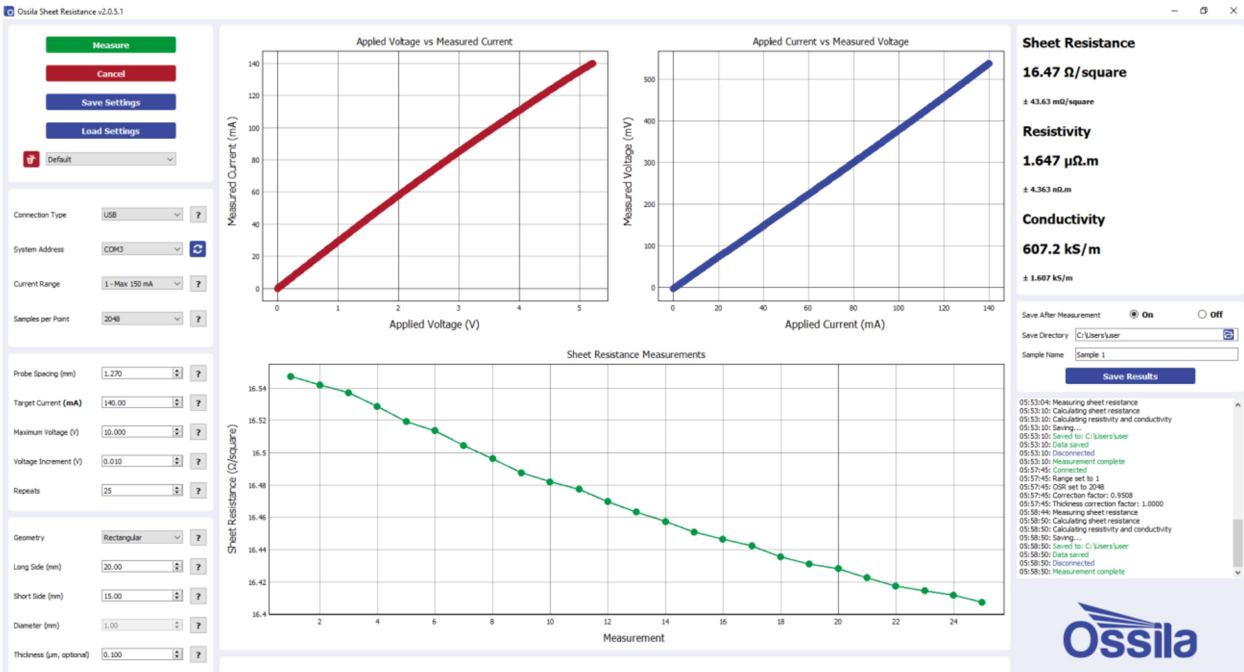

Figure 3.3: Sheet resistivity of ITO at 140mA target current.

The results shown in figure 3.3 above are:

- Sheet resistance = 16.47 Ω/square
- Resistivity = 1.647 µΩ.m
- Conductivity = 607.2 kS/m

Now, let us decrease the target current to 60mA and measure the sheet resistivity of ITO without changing the current range (1 – Max 150 mA) and other parameters.

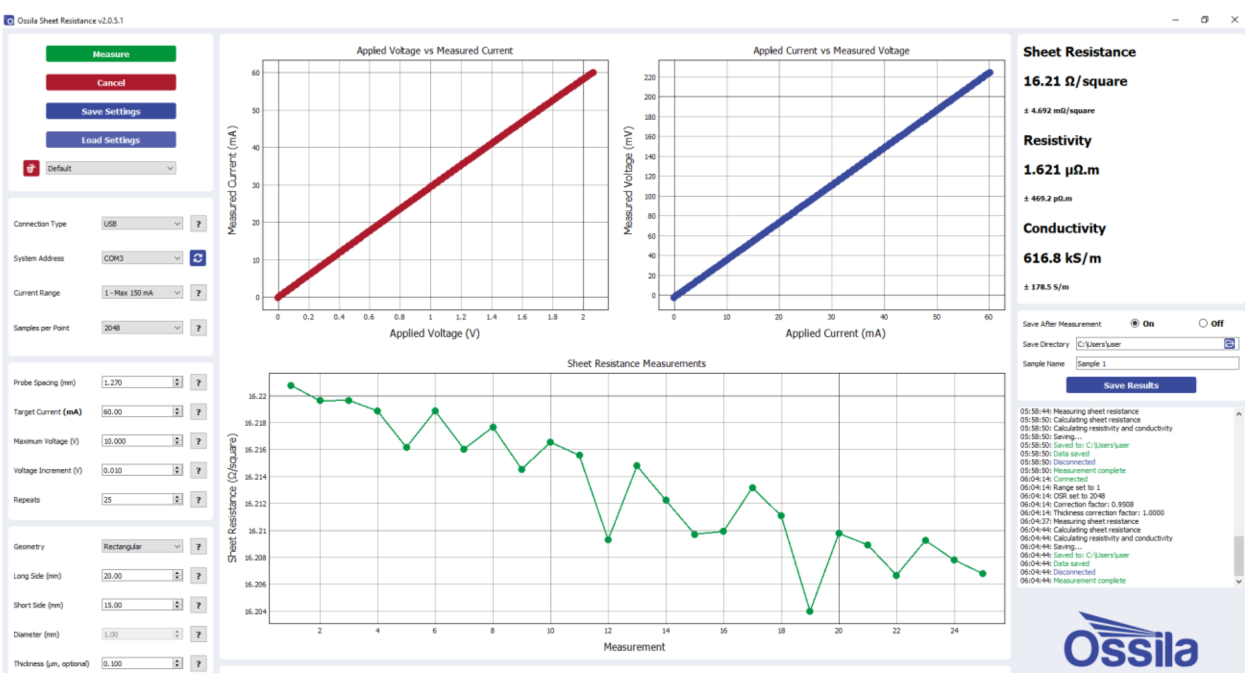

Figure 3.4: Sheet resistivity of ITO at 60mA target current.

The results shown in figure 3.4 above are:

- Sheet resistance = 16.21 Ω/square
- Resistivity = 1.621 µΩ.m
- Conductivity = 616.8 kS/m

If we change the current range, sheet resistance and resistivity will decrease and conductivity increases more. Let us measure only for the current range of 4 – Max 200 µA and target current 100µA and see what will happen.

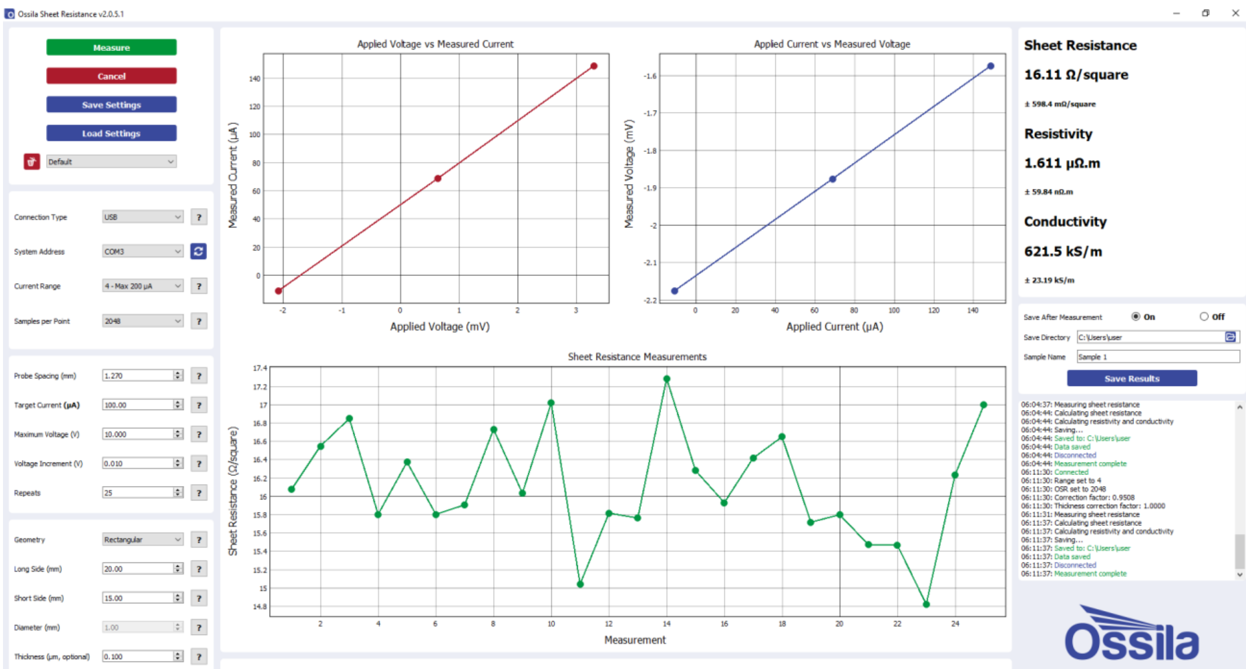

Figure 3.5: Sheet resistivity of ITO at 100µA target current and current range 4 – Max 200µA.

The results shown in figure 3.5 above are:

- Sheet resistance = 16.11 Ω/square
- Resistivity = 1.611 µΩ.m
- Conductivity = 621.5 kS/m

Let us set the target current to -100mA in the current range of 1- Max 150mA and see what will happen.

The results shown in figure 3.6 below are:

- Sheet resistance = 16.11 Ω/square
- Resistivity = 1.611 µΩ.m
- Conductivity = 621.5 kS/m

Questions

1. What do you observe? Does the target current affect the sheet resistivity of ITO?
2. What change do you observe on the sheet resistance measurement graph?

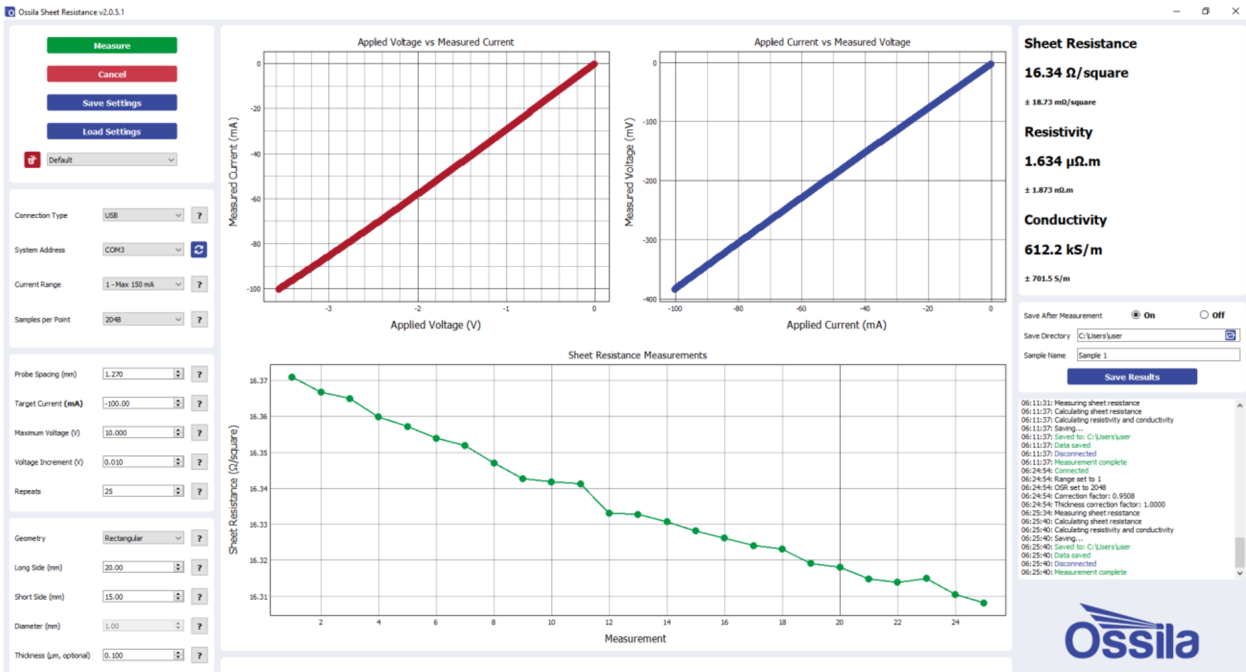

Figure 3.6: Sheet resistivity of ITO at -100mA target current.

3.4 Maximum voltage

The default Maximum voltage is 10V. Let us measure the sheet resistivity of the ITO setting the thickness 100nm (0.1µm) and leaving other parameters unchanged or as default. This would have the same result as figure 3.0 which are:

- Sheet resistance = 16.3 Ω/square
- Resistivity = 1.63 µΩ.m
- Conductivity = 613.6 kS/m

Now, let us decrease the maximum voltage to 5V and measure the sheet resistivity of ITO without changing other parameters.

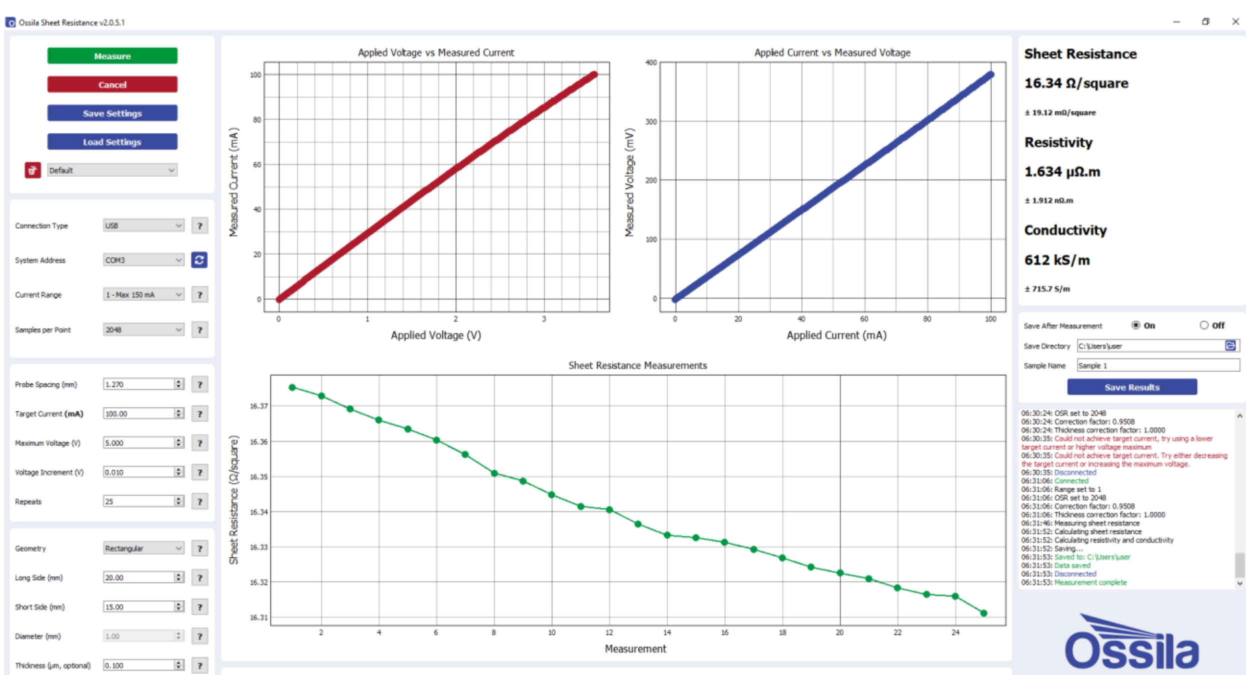

Figure 3.7: Sheet resistivity of ITO at 5V maximum voltage.

The results shown in figure 3.7 above are:

- Sheet resistance = 16.34 Ω/square
- Resistivity = 1.634 μΩ.m
- Conductivity = 612.2 kS/m

Questions

1. What do you observe? Does the maximum voltage affect the sheet resistivity of ITO?
2. What will happen if we further decrease the voltage?