Electrical Characterization of Photovoltaic Materials and Solar Cells with the 4200A-SCS Parameter Analyzer

I-V, C-V, C-f, DLCP, Pulsed I-V, Resistivity, and Hall Voltage Measurements

APPLICATION NOTE

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Introduction

The increasing demand for clean energy and the largely untapped potential of the sun as an energy source is making solar energy conversion technology increasingly important. As a result, the demand for solar cells, which convert sunlight directly into electricity, is growing. Solar or photovoltaic (PV) cells are made up of semiconductor materials that absorb photons from sunlight and then release electrons, causing an electric current to flow when the cell is connected to a load. A variety of measurements are used to characterize a solar cell's performance, including its output and its efficiency. This electrical characterization is performed as part of research and development of photovoltaic cells and materials, as well as during the manufacturing process.

Some of the electrical tests commonly performed on solar cells involve measuring current and capacitance as a function of an applied DC voltage. Capacitance measurements are sometimes made as a function of frequency or AC voltage. Some tests require pulsed current-voltage measurements. These measurements are usually performed at different light intensities and under different temperature conditions. A variety of important device parameters can be extracted from the DC and pulsed current-voltage (I-V) and capacitance-voltage (C-V) measurements, including output current, conversion efficiency, maximum power output, doping density, resistivity, etc. Electrical characterization is important in determining how to make the cells as efficient as possible with minimal losses.

Instrumentation such as the 4200A-SCS Parameter Analyzer can simplify testing and analysis when making these critical electrical measurements. The 4200A-SCS is an integrated system that includes instruments for making DC and ultra fast I-V and C-V measurements, as well as control software, graphics, and mathematical analysis capability. The 4200A-SCS is well-suited for performing a wide range of measurements, including DC and pulsed current-voltage (I-V), capacitance-voltage (C-V), capacitance-frequency (C-f), drive level capacitance profiling (DLCP), four-probe resistivity (ρ, σ), and Hall voltage (V_H) measurements. This application note describes how to use the 4200A-SCS to make these electrical measurements on PV cells.

Making Electrical Measurements with the 4200A-SCS

To simplify testing photovoltaic materials and cells, the 4200A-SCS is supported with tests and a project for making many of the mostly commonly used measurements easily. These tests, which include I-V, capacitance, and resistivity measurements, also include formulas for extracting common parameters such as the maximum power, short circuit current, defect density, etc. The *SolarCell* project (**Figure 1**) is included with all 4200A-SCS systems and can be found in the Project Library if you use the PV cell filter. Most of the tests in this project can also be found in the Test Library.

Table 1. Tests in the *SolarCell* project

Measurement	Name	Description
DC I-V	*fwd-ivsweep*	Performs I-V sweep and calculates I_{sc}, V_{oc}, P_{max}, I_{max}, V_{max}, FF
	rev-ivsweep	Performs reversed bias I-V sweep
Capacitance	*solarcell-cvsweep*	Generates C-V sweep
	solarcell-c-2vsv	Generates C-V sweep and calculates $1/C^2$
	cfsweep	Sweeps the frequency and measures capacitance
	dlcp	Measures capacitance as AC voltage is swept. DC voltage is applied so as to keep the total applied voltage constant. The defect density is calculated.
Pulse-IV	*solarcell-pulse-iv-sweep*	Performs pulse I-V sweep using one channel of PMU
4-Probe Resistivity	*hir*	Uses 3 or 4 SMUs to source current and measure voltage difference for high resistance semiconductor materials. Calculates sheet resistivity.
	lor	Uses 1 or 2 SMUs to source current and measure voltage using remote sense. Calculates sheet resistivity. Uses current reversal method to compensate for thermoelectric voltage offsets.
vdp Resistivity	*i1-v23*	First of 4 tests that are used to measure the van der Pauw resistivity. This test sources current between terminals 1 and 4 and measures the voltage difference between terminals 2 and 3.
	i2-v34	Sources current between terminals 2 and 1 and measures the voltage difference between terminals 3 and 4.
	i3-v41	Sources current between terminals 3 and 2 and measures the voltage difference between terminals 4 and 1.
	i4-v12	Sources current between terminals 4 and 1 and measures the voltage difference between terminals 1 and 2.

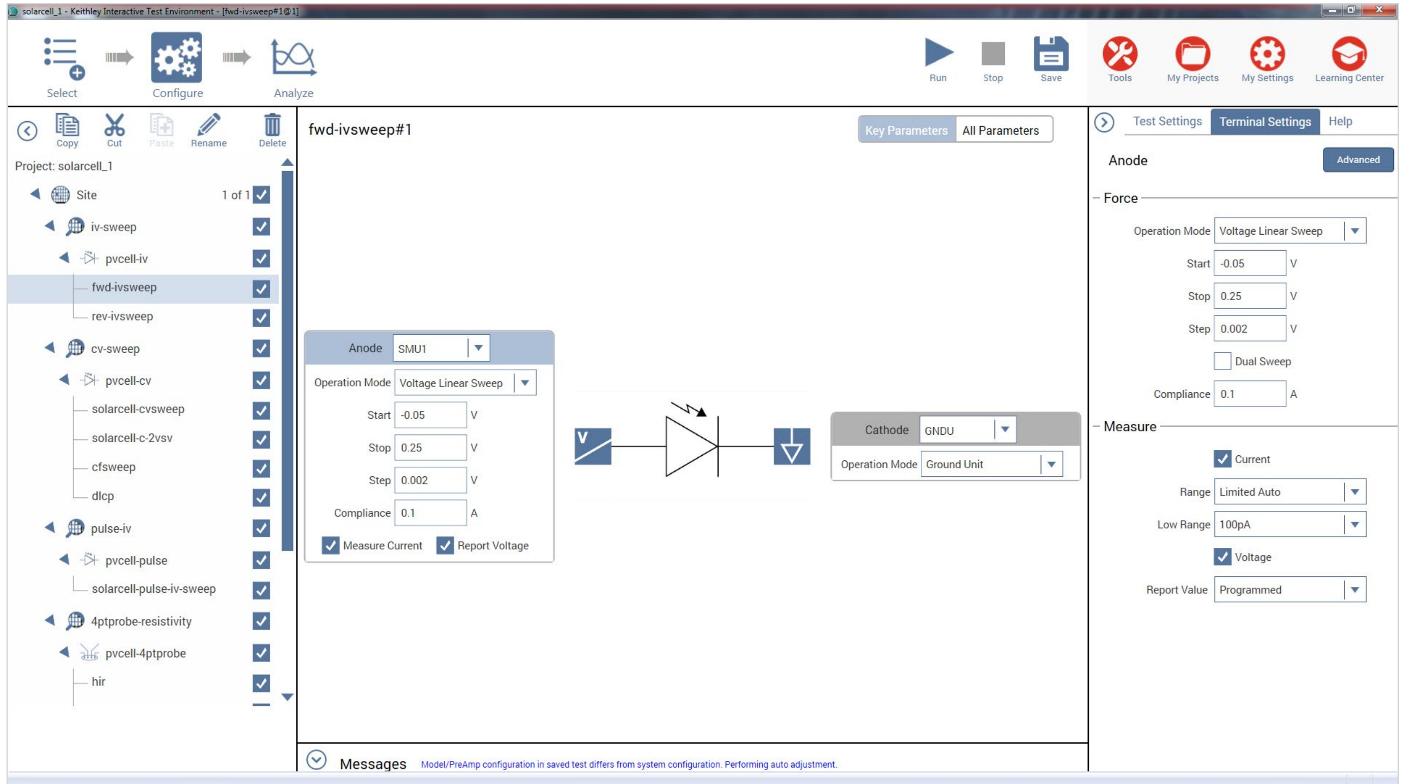

Figure 1. Screenshot of *Solar Cell* project for the 4200A-SCS

DC Current-Voltage (I-V) Measurements

As described previously, many solar cell parameters can be derived from current-voltage (I-V) measurements of the cell. These I-V characteristics can be measured using the 4200A-SCS's Source-Measure Units (SMUs), which can source and measure both current and voltage. Because these SMUs have four-quadrant source capability, they can sink the cell current as a function of the applied voltage. Four types of SMUs are available for the 4200A-SCS: the 4200-SMU or 4201-SMU, which can source/sink up to 100 mA, and the 4210-SMU or 4211-SMU, which can source/sink up to 1 A. If the output current of the cell exceeds these current levels, it may be necessary to reduce it, possibly by reducing the area of the cell itself. However, if this is not possible, Keithley's SourceMeter® instruments, which are capable of sourcing/sinking higher currents, offer possible alternative solutions.

Parameters Derived from I-V Measurements

A solar cell may be represented by the equivalent circuit model shown in **Figure 2**, which consists of a light-induced current source (I_L), a diode that generates a saturation current [$I_S(e^{qV/kT} - 1)$], series resistance (r_s), and shunt resistance (r_{sh}). The series resistance is due to the resistance of the metal contacts, ohmic losses in the front surface of the cell, impurity concentrations, and junction depth. The series resistance is an important parameter because it reduces both the cell's short-circuit current and its maximum power output. Ideally, the series resistance should be 0 Ω ($r_s = 0$). The shunt resistance represents the loss due to surface leakage along the edge of the cell or to crystal defects. Ideally, the shunt resistance should be infinite ($r_{sh} = \infty$).

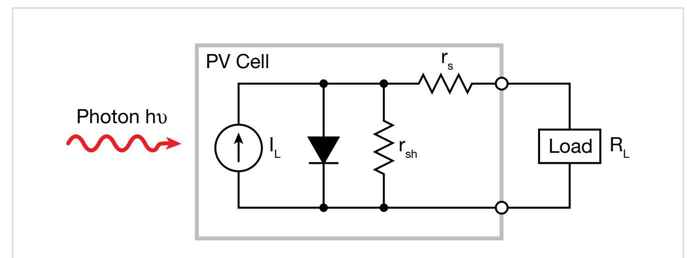

Figure 2. Idealized equivalent circuit of a photovoltaic cell

If a load resistor (R_L) is connected to an illuminated solar cell, then the total current becomes:

$$I = I_S(e^{qV/kT} - 1) - I_L$$

where:

I_S = current due to diode saturation

I_L = current due to optical generation

Several parameters are used to characterize the efficiency of the solar cell, including the maximum power point (P_{max}), the energy conversion efficiency (η), and the fill factor (FF). These points are illustrated in **Figure 3**, which shows a typical forward bias I-V curve of an illuminated PV cell. The maximum power point (P_{max}) is the product of the maximum cell current (I_{max}) and the voltage (V_{max}) where the power output of the cell is greatest. This point is located at the "knee" of the curve.

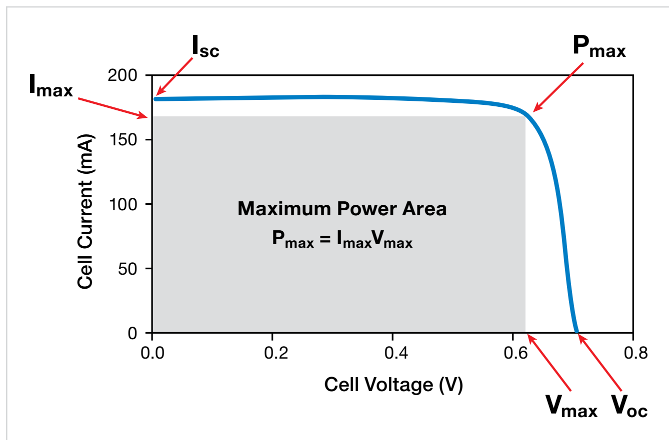

Figure 3. Typical forward bias I-V characteristics of a PV cell

The fill factor (FF) is a measure of how far the I-V characteristics of an actual PV cell differ from those of an ideal cell. The fill factor is defined as:

$$FF = \frac{I_{max}V_{max}}{I_{sc}V_{oc}}$$

where:

I_{max} = the current at the maximum power output (A)

V_{max} = the voltage at the maximum power output (V)

I_{sc} = the short-circuit current (A)

V_{oc} = the open-circuit voltage (V)

As defined, the fill factor is the ratio of the maximum power ($P_{max} = I_{max}V_{max}$) to the product of the short circuit current (I_{sc}) and the open circuit voltage (V_{oc}). The ideal solar cell has a fill factor equal to one (1) but losses from series and shunt resistance decrease the efficiency.

Another important parameter is the conversion efficiency (η), which is defined as the ratio of the maximum power output to the power input to the cell:

$$\eta = \frac{P_{max}}{P_{in}}$$

where:

P_{max} = the maximum power output (W)

P_{in} = the power input to the cell defined as the total radiant energy incident on the surface of the cell (W)

Making Connections to the Solar Cell for I-V Measurements

Figure 4 illustrates a solar cell connected to the 4200A-SCS for I-V measurements. One side of the solar cell is connected to the Force and Sense terminals of SMU1; the other side is connected to the Force and Sense terminals of either SMU2 or the ground unit (GNDU) as shown.

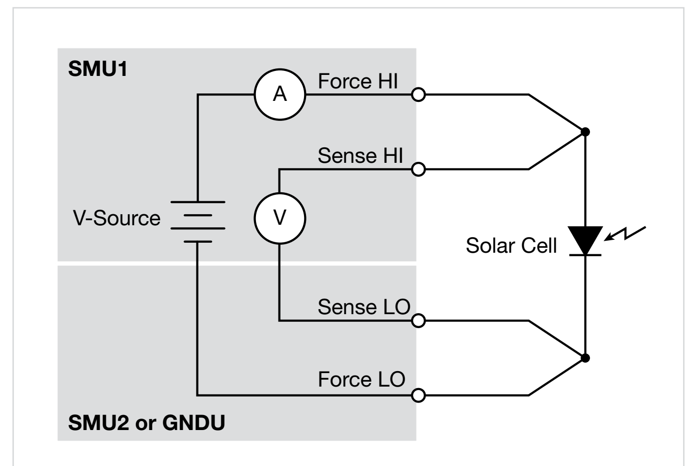

Figure 4. Connection of 4200A-SCS to a solar cell for I-V measurements

Using a four-wire connection eliminates the lead resistance that would otherwise affect this measurement's accuracy. With the four-wire method, a voltage is sourced across the solar cell using one pair of test leads (between Force HI and Force LO), and the voltage drop across the cell is measured across a second set of leads (across Sense HI and Sense

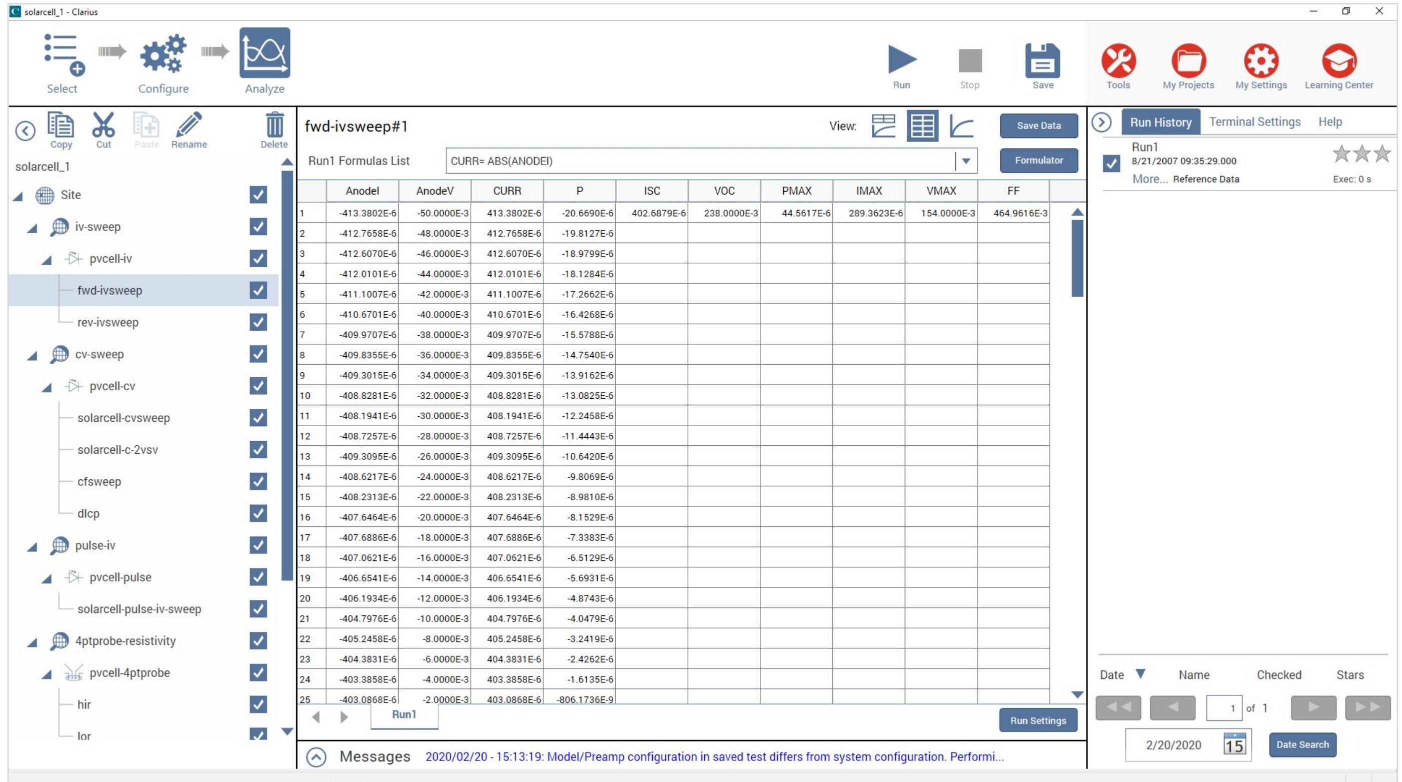

Figure 5. Results of calculated parameters shown in the Sheet in the Analyze pane.

LO). The sense leads ensure that the voltage developed across the cell is the programmed output value and compensate for the lead resistance.

Forward-Biased I-V Measurements

Forward-biased I-V measurements of the solar cell are made under controlled illumination. The SMU is set up to output a voltage sweep and measure the resulting current. This forward bias sweep can be performed using the *Solar Cell Forward I-V Sweep* or "*fwd-ivsweep*" test, which allows adjusting the sweep voltage to the desired values. As previously illustrated in **Figure 3**, the voltage source is swept from $V_1 = 0$ to $V_2 = V_{OC}$. When the voltage source is 0 ($V_1 = 0$), the current is equal to the source-circuit current ($I_1 = I_{SC}$). When the voltage source is an open circuit ($V_2 = V_{OC}$) then the current is equal to zero ($I_2 = 0$). The parameters, V_{OC} and I_{SC} can be derived easily from the sweep data using the 4200A-SCS's built-in mathematical analysis tool, the Formulator. For convenience, the *Solar Cell Forward I-V Sweep* test has the commonly derived parameters already calculated, so the values automatically appear in the Sheet in the Analyze pane every time the test is executed. **Figure 5** shows some of the derived parameters in the Sheet. These parameters include the short-circuit current (I_{SC}), the open circuit voltage (V_{OC}), the maximum power point (P_{max}), the maximum cell current (I_{max}), the maximum cell voltage (V_{max}), and the fill factor (FF).

The user can easily add other formulas depending on the required parameters that need to be determined.

Using the Formulator, the conversion efficiency (η) can also be calculated if the user knows the power input to the cell and inputs the formula. The current density (J) can also be derived by using the Formulator and inputting the area of the cell.

Figure 6 shows an actual I-V sweep of an illuminated silicon PV cell generated with the 4200A-SCS using the "*fwd-ivsweep*" test. Because the system's SMUs can sink current, the curve passes through the fourth quadrant and allows power to be extracted from the device (I–, V+). If the current output spans several decades as a function of the applied voltage, it may be desirable to generate a semilog plot of I vs. V. The Graph supports an easy transition between displaying data graphically on either a linear or a log scale.

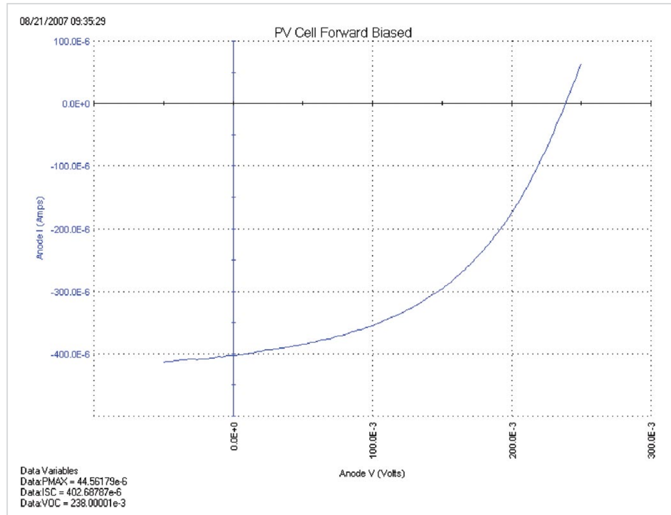

Figure 6. I-V sweep of silicon PV cell generated with the 4200-SMU

If desired, the graph settings functions make it easy to create an inverted version of the graph about the voltage axis. Simply go to the Graph Settings tab, select Axis Properties, select the Y1 Axis tab, and click on the Invert checkbox. The inverse of the graph will appear as shown in **Figure 7**.

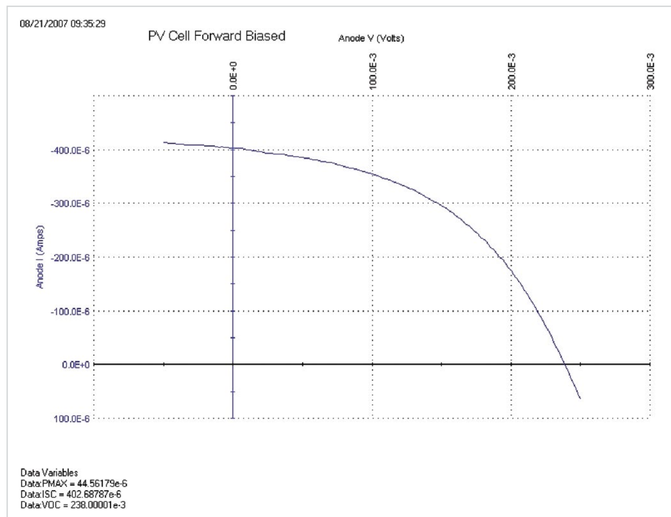

Figure 7. Inversion of the forward-biased I-V curve about the voltage axis

The series resistance (r_s) can be determined from the forward I-V sweep at two or more light intensities. First, make I-V curves at two different intensities (the magnitudes of the intensities are not important). Measure the slope of this curve from the far forward characteristics where the curve becomes linear. The inverse of this slope yields the series resistance:

$$r_s = \frac{\Delta V}{\Delta I}$$

By using additional light intensities, this technique can be extended using multiple points located near the knee of the curves. As illustrated in **Figure 8**, a line is generated from which the series resistance can be calculated from the slope.

When considered as ammeters, one important feature of the SMUs is their very low voltage burden. The voltage burden is the voltage drop across the ammeter during the measurement. Most conventional digital multimeters (DMMs) will have a voltage burden of at least 200 mV at full scale. Given that only millivolts may be sourced to the sample in solar cell testing, this can cause large errors. The 4200A-SCS's SMUs don't produce more than a few hundred microvolts of voltage burden, or voltage drop, in the measurement circuit.

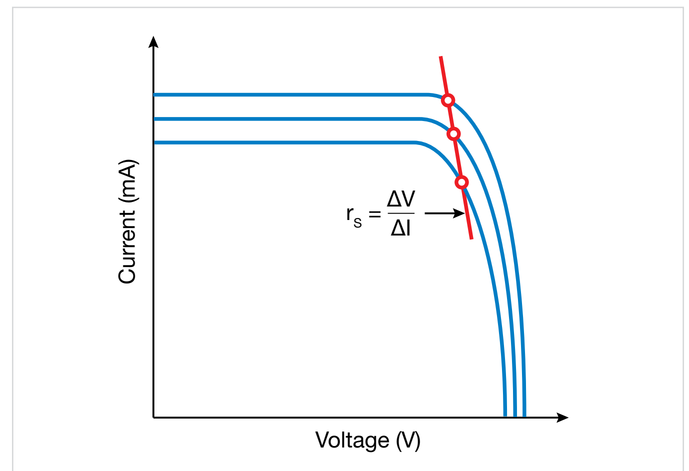

Figure 8. Slope method used to calculate the series resistance

Reverse-Biased I-V Measurements

The leakage current and shunt resistance (r_{sh}) can be derived from the reverse-biased I-V data. Typically, the test is performed in the dark. The voltage is sourced from 0V to a voltage level where the device begins to break down. The resulting current is measured and plotted as a function of the voltage. Depending on the size of the cell, the leakage current can be as small as picoamps. The SMUs have a preamp option that allows making accurate measurements well below a picoamp. When making very sensitive low current measurements (nanoamps or less), use low noise cables and place the device in a shielded enclosure to shield it electrostatically. This conductive shield is connected to the Force LO terminal of the 4200A-SCS. The Force LO terminal connection can be made from the outside shell of the triax

connectors, the black binding post on the ground unit (GNDU), or from the Force LO triax connector on the GNDU.

One method for determining the shunt resistance of the PV cell is from the slope of the reverse-biased I-V curve, as shown in **Figure 9**. From the linear region of this curve, the shunt resistance can be calculated as:

$$r_{sh} = \frac{\Delta V_{Reverse\ Bias}}{\Delta I_{Reverse\ Bias}}$$

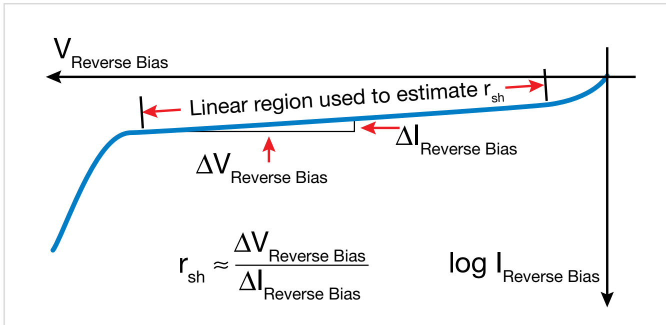

Figure 9. Typical reverse-biased characteristics of a PV cell

Figure 10 shows an actual curve of a reverse-biased solar cell, generated using the *Solar Cell Reverse I-V Sweep* or "*rev-ivsweep*" test. In this semi-log graph, the absolute value of the current is plotted as a function of the reverse-biased voltage that is on an inverted x-axis.

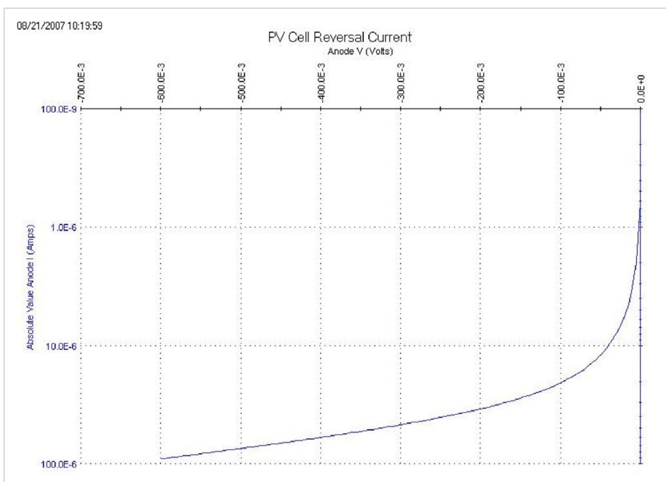

Figure 10. Reverse-biased I-V measurement of silicon solar cell using the SMU

Capacitance Measurements

Capacitance-voltage measurements are useful in deriving particular parameters about PV devices. Depending on the type of solar cell, capacitance-voltage (C-V) measurements can be used to derive parameters such as the doping concentration and the built-in voltage of the junction. A capacitance-frequency (C-f) sweep can be used to provide information on the existence of traps in the depletion region. The 4210-CVU or 4215-CVU, the 4200A-SCS's optional capacitance meter, can measure the capacitance as a function of an applied DC voltage (C-V), a function of frequency (C-f), a function of time (C-t), or a function of the AC voltage. The CVU can also measure conductance and impedance.

To make capacitance measurements, a solar cell is connected to the CVU as shown in **Figure 11**. Like I-V measurements made with the SMU, the capacitance measurements also involve a four-wire connection to compensate for lead resistance. The HPOT/HCUR terminals are connected to the anode and the LPOT/LCUR terminals are connected to the cathode. This connects the high DC voltage source terminal of the CVU to the anode.

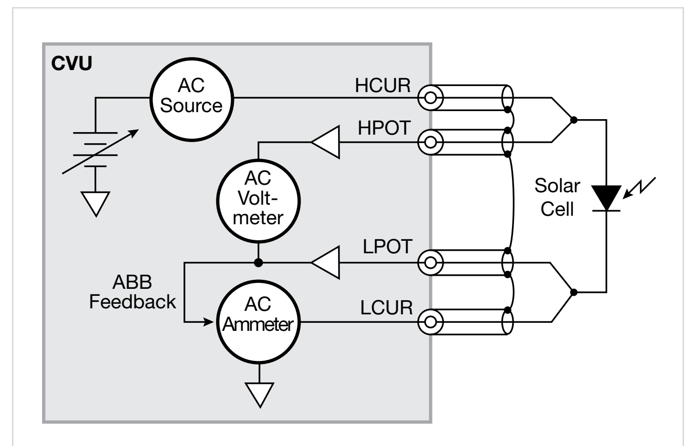

Figure 11. Connecting the solar cell to the CVU capacitance meter

Figure 11 shows the shields of the four coax cables coming from the four terminals of the capacitance meter. The shields from the coax cables must be connected together as close as possible to the solar cell to obtain the highest accuracy because this reduces the effects of the inductance in the measure circuit. This is especially important for capacitance measurements made at higher test frequencies.

Performing an Open and Short Connection Compensation will reduce the effects of cable capacitance on measurement accuracy. This simple procedure is described in the 4200A-SCS Reference Manual.

Given that the capacitance of the cell is directly related to the area of the device, it may be necessary to reduce the area of the cell itself, if possible, to avoid capacitances that may be too high to measure. Also, setting the CVU to measure capacitance at a lower test frequency and/or lower AC drive voltage will allow measuring higher capacitances.

C-V Sweep

C-V measurements can be made either forward-biased or reverse-biased. However, when the cell is forward-biased, the applied DC voltage must be limited; otherwise, the conductance may get too high for the capacitance meter to measure. The maximum DC current cannot be greater than 10 mA; otherwise, the instrument's DC voltage source will go into compliance and the DC voltage output will not be at the desired level.

Figure 12 illustrates a C-V curve of a silicon solar cell generated by the CVU using the *Solar Cell C-V Sweep* or "*solarcell-cvsweep*" test. This test was performed in the dark while the cell was reversed-biased.

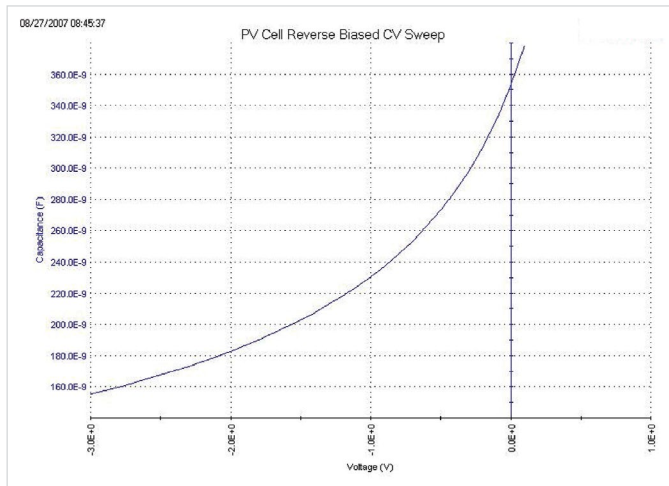

Figure 12. C-V sweep of a silicon solar cell

Rather than plotting dC/dV, it is sometimes desirable to view the data as $1/C^2$ vs. voltage because some parameters are related to the $1/C^2$ data. For example, the doping density (N) can be derived from the slope of this curve because N is related to the capacitance by:

$$N(a) = \frac{2}{qE_S A^2[d(1/C^2)/dV]}$$

where:

N(a) = the doping density ($1/cm^3$)

q = the electron charge (1.60219×10^{-19}C)

E_S = semiconductor permittivity (1.034×10^{-12}F/cm for silicon)

A = area (cm^2)

C = measured capacitance (F)

V = applied DC voltage (V)

The built-in voltage of the cell junction can be derived from the intersection of the $1/C^2$ curve and the horizontal axis. This plot should be a fairly straight line. An actual curve taken with the CVU, generated using the *Solar Cell I/C² C-V Sweep* or "*solarcell-c-2vsv*" test, is shown in **Figure 13**. The Formulator function is used to derive both the doping density (N) and the built-in voltage on the x-axis (x-intercept). The doping density is calculated as a function of voltage in the Formulator and appears in the Sheet in the Analyze pane. The user must input the area of the cell in the Constants area of the Formulator. The built-in voltage source value is derived both in the Formulator and by using a Linear Line Fit option in the Graph settings. Notice the value of the x-intercept appears in the lower left corner of the graph.

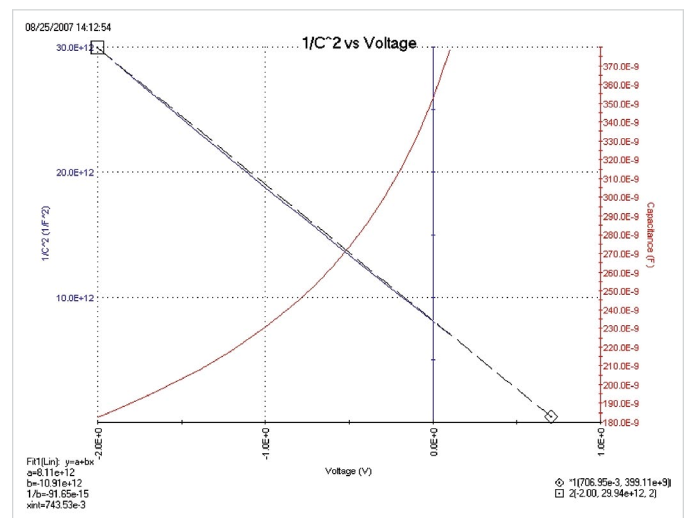

Figure 13. $1/C^2$ vs. voltage of a silicon solar cell

C-f Sweep

The CVU option can also measure capacitance, conductance, or impedance as a function of the test frequency. The range of frequency is from 1 kHz to 10 MHz. The curve in **Figure 14** was generated by using the Solar Cell C-f Sweep or "*cfsweep*" test. Both the range of sweep frequency and the bias voltage can be adjusted. The desired parameters, such as the trap densities, can be extracted from the capacitance vs. frequency data. The measurements can be repeated at various temperatures.

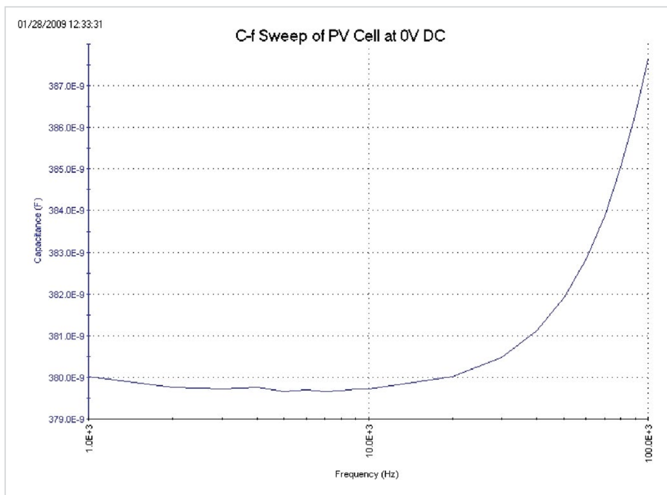

Figure 14. C-f Sweep of Solar Cell

Drive Level Capacitance Profiling (DLCP)

Drive Level Capacitance Profiling (DLCP) is a technique for determining the defect density (N_{DL}) as a function of depth of a photovoltaic cell[1]. During the DLCP measurement, the applied AC voltage (peak-to-peak) is swept and the DC voltage is varied while the capacitance is measured. This is in contrast to the conventional C-V profiling technique, in which the AC rms voltage is fixed and the DC voltage is swept.

In DLCP, the DC voltage is automatically adjusted to keep the total applied voltage (AC + DC) constant while the AC voltage is swept. By maintaining a constant total bias, the exposed charge density (ρ_e) inside the material stays constant up to a fixed location (x_e), which is defined as the distance from the interface where $E_F - E_v = E_e$. This is also in contrast to conventional C-V profiling, the analysis of which assumes that the only charge density changes occur at the end of the depletion region.[1]

Thus, in DLCP, the position (x_e) can be varied by adjusting the DC voltage bias to the sample. This also allows determining the defect density as a function of the distance, or special profiling. The test frequency and temperature of the measurement can also be varied to show a profile that is energy dependent.

Once the measurements are taken, a quadratic fit of the C-V data is related to the impurity density at a given depletion depth as follows for a p-type semiconductor:

$$N_{DL} \equiv \frac{C_0^3}{2q\varepsilon A^2 C_1} = \frac{|\rho_e|}{q} = p + \int_{E_F^0}^{E_V + E_e} g(E, x_e)\, dE$$

where:

N_{DL} = defect density (cm^{-3})

C_1, C_0 = coefficients of quadratic fit of C-V data

q = electron charge (1.60×10^{-19}C)

ε = permittivity (F/cm)

A = area of solar cell (cm^2)

ρ_e = charge density (C/cm^3)

p = hole density (cm^{-3})

x_e = distance from interface where $E_F - E_v = E_e$

The coefficients C_0 and C_1 are determined via a full least-squares best fit of the data to a quadratic equation:

$$dQ/dV = C_2\,(dV)^2 + C_1{*}(dV) + C_0$$

However, only the C_0 and C_1 coefficients are used in the analysis.

The *Solar Cell DLCP* or "*dlcp*" test allows making C-V measurements for drive level capacitance profiling. During these measurements, the total applied voltage remains constant as the DC voltage bias is automatically adjusted as the AC voltage drive level amplitude varies. The AC amplitude can be adjusted from 10 mVrms to 100 mVrms (14.14 mV to 141.4 mVp-p). The range of frequency can also be set from 1 kHz to 10 MHz. The capacitance is measured as the AC voltage is sweeping.

1 J. T. Heath, J. D. Cohen, W. N. Shafarman, "Bulk and metastable defects in CuIn1–xGaxSe2 thin films using drive-level capacitance profiling," Journal of Applied Physics, vol. 95, no. 3, p. 1000, 2004

Table 2 lists the input parameters used in the test, the allowed range of input values, and descriptions. This test was created from the DLCP User Library and the ACSweep User Module. The user inputs the total applied voltage (VmaxTotal), the AC start, stop, and step voltages (VacppStart, VacppStop, and VacppStep), the time between voltage steps (SweepDelay), the test frequency (Frequency), the measurement speed (Speed), the measurement range (CVRange), and offset compensation (OpenComp, ShortComp, LoadComp, and LoadVal).

Table 2. Adjustable parameters for the *dlcp* test (ACSweep User Module)

Parameter	Range	Description
VmaxTotal	–10 to 10 volts	Applied DC Volts and ½ AC Volts p-p
VacppStart	.01414 to .1414	Start Vac p-p
VacppStop	.02828 to .1414	Stop Vac p-p
VacppStep	.0007070 to .1414	Step Vac p-p
SweepDelay	0 to 100	Sweep delay time in seconds
Frequency	1E+3 to 10E+6	Test Frequency in Hertz
Speed	0, 1, 2	0=Fast, 1=Normal, 2=Quiet
CVRange	0, 1E–6, 30E–6, 1E–3	0=autorange, 1 µA, 30 µA, 1 mA
OpenComp	1, 0	Enables/disables open compensation for CVU
ShortComp	1, 0	Enables/disables short compensation for CVU
LoadComp	1, 0	Enables/disables load compensation for CVU
LoadVal	1 to 1E+9	Load value

Once the test is executed, the capacitance, AC voltage, DC voltage, time stamp, frequency, and the defect density (N_{DL}) are determined and their values are listed in the Sheet. The defect density is calculated in the Formulator using a quadratic line fit of the C-V data. The coefficients (C_0 and C_1) of the quadratic equation are also listed in the Sheet. The user inputs the area and permittivity of the solar cell to be tested into the Constants/Values/Units area of the Formulator.

Figure 15 shows the measurement results in the graph of capacitance vs. AC voltage p-p. Notice the coefficients of the derived quadratic line fit and the defect density are displayed on the graph.

The capacitance measurements can be repeated at various applied total voltages in order to vary the position of x_e. The energy (E_e) can be varied by changing the test frequency (1 kHz to 10 MHz) or the temperature. To change the temperature of the measurement, the user can add an Action to the project to control a temperature controller via the 4200A-SCS's GPIB interface. The 4200A-SCS is provided with user libraries for operating the Temptronics, Lakeshore, and Triotek temperature controllers.

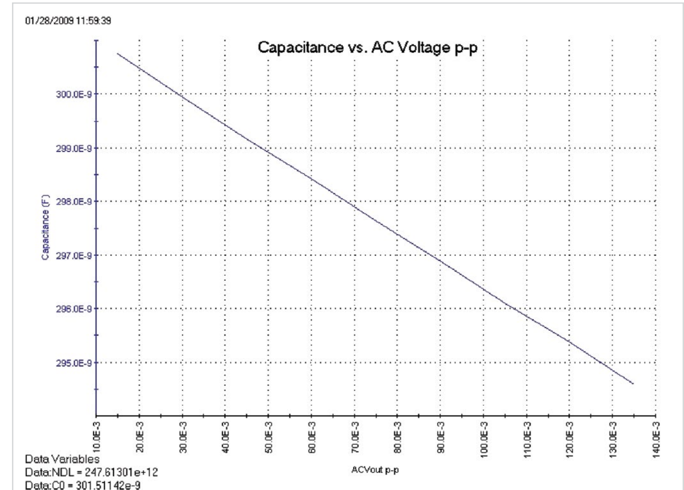

Figure 15. Capacitance vs. AC voltage p-p of a solar cell

Pulsed I-V Measurements

Pulsed I-V measurements can be useful for studying parameters of solar cells. In particular, pulsed I-V measurements have been used to determine the conversion efficiency, minimum carrier lifetime, and the effects of cell capacitance. The 4225-PMU, the 4200A-SCS's optional Ultra-Fast I-V Module, can output pulsed voltage and measure current, and can capture ultra-high-speed current or voltage waveforms in the time domain. In addition to sourcing a pulsed voltage, the PMU can sink current so it can measure a solar cell's current output.

To make pulsed I-V measurements on a solar cell, the 4225-PMU is connected to the cell as shown in **Figure 16**. Each PMU has two channels so the solar cell can be connected using either one or two channels. In the one-channel case shown, one end of the cell is connected to the HI terminal of PMU CH1 and the other side of the cell is connected to the shield of the coax cable, which is the LO terminal of the PMU.

Unlike the DC I-V and C-V measurements, the 4225-PMU uses a two-wire technique. The Short Compensation feature can be used to "zero out" the voltage drops due to the cables so that a 4-wire measurement technique isn't necessary.

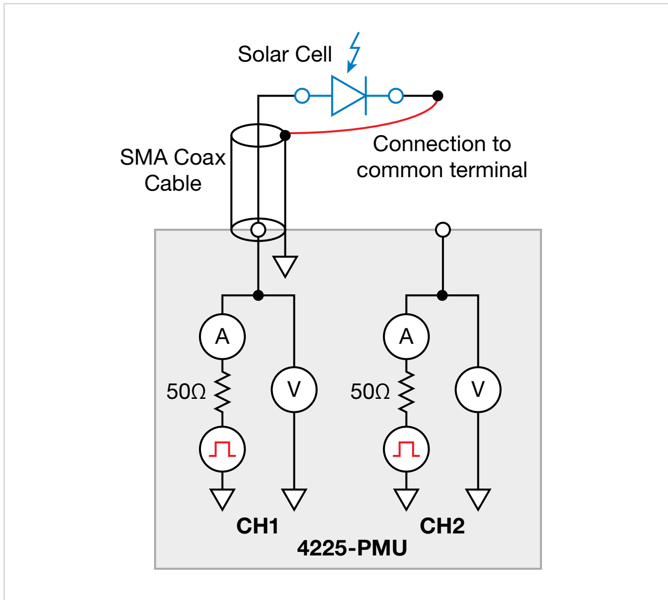

Figure 16. Connecting the solar cell to the 4225-PMU Ultra-Fast I-V Module

Because solar cells are fairly capacitive, it is important to ensure the pulse width is long enough for the pulsed I-V sweep. The waveform capture mode should be used to verify the pulse width prior to generating the pulsed I-V sweep. The waveform capture mode enables a time-based current and/or voltage measurement that is typically the capture of a pulsed waveform. This can be used to perform a dynamic test on the cell or used as a diagnostic tool for choosing the appropriate pulse settings in the pulsed I-V mode. Given that larger solar cells have larger capacitances, it may be necessary to reduce the area of the cell itself to avoid a long settling time in the measurement.

The results of generating a pulsed I-V measurement sweep on a silicon solar cell are shown in **Figure 17**. Note that the current is in the fourth quadrant of the curve. This indicates that the PMU is sinking current; in other words, the current is flowing out of the solar cell and into the PMU.

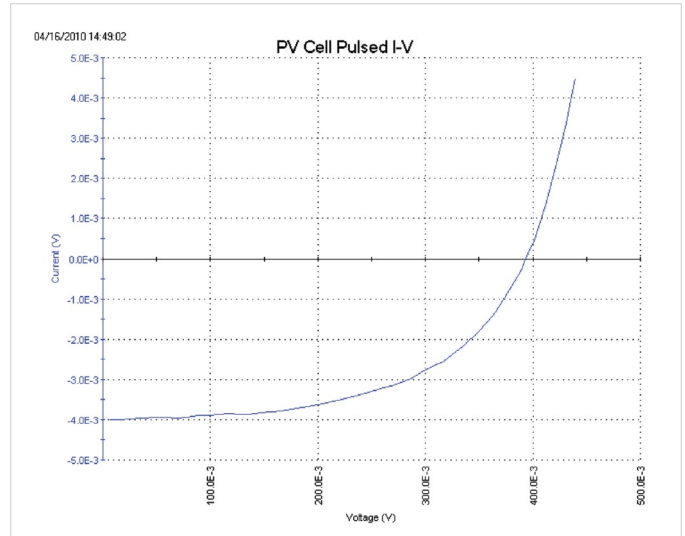

Figure 17. Pulsed I-V measurement on solar cell using 4225-PMU

Resistivity and Hall Voltage Measurements

Determining the resistivity of a solar cell material is a common electrical measurement given that the magnitude of the resistivity directly affects the cell's performance. Resistivity measurements of semiconductor materials are usually performed using a four-terminal technique. Using four probes eliminates errors due to the probe resistance, spreading resistance under each probe, and the contact resistance between each metal contact and the semiconductor material. Two common techniques for determining the resistivity of a solar cell material are the four-point collinear probe method and the van der Pauw method. The *SolarCell* project contains several tests for making both types of measurements, which are described in the next few paragraphs.However, the Test Library also contains individual tests for making both van der Pauw and Hall coefficient measurements. These tests can be found by typing in the name of these tests in the search bar in the Select view: vdp-surface-resistivity, vdp-volume-resistsivity, or hall-coefficient. These tests are described in the Keithley application note, "Making van der Pauw Resistivity and Hall Voltage Measurements Using the 4200A-SCS Parameter Analyzer".

Four-Point Collinear Probe Measurement Method

The four-point collinear probe technique involves bringing four equally spaced probes in contact with a material of unknown resistance. The probe array is placed in the center of the material as shown in **Figure 18**. The two outer probes are used to source current and the two inner probes are used to measure the resulting voltage difference across the surface of the material.

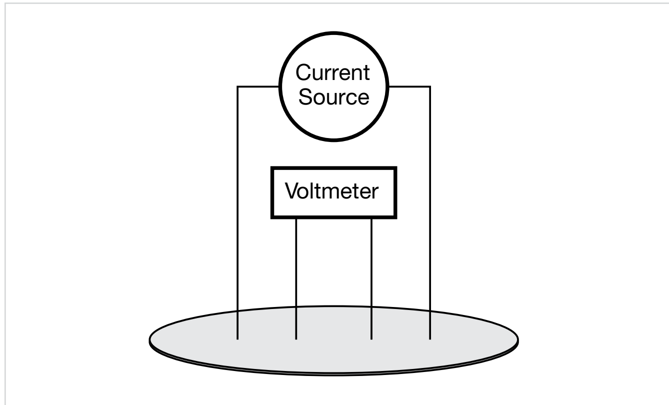

Figure 18. Four-point collinear probe resistivity configuration

From the sourced current and the measured voltage, the surface or sheet resistivity is calculated by:

$$\sigma = \frac{\pi}{\ln 2} \times \frac{V}{I}$$

where:

σ = surface resistivity (Ω/☐)

V = the measured voltage (V)

I = the source current (A)

Note that the units for sheet resistivity are expressed as ohms per square (Ω/☐) in order to distinguish this number from the measured resistance (V/I), which is simply expressed in ohms. Correction factors to the resistivity calculation may be required for extremely thin or thick samples or if the diameter of the sample is small relative to the probe spacing.

If the thickness of the sample is known, the volume resistivity can be calculated as follows:

$$\rho = \frac{\pi}{\ln 2} \times \frac{V}{I} \times t \times k$$

where:

ρ = volume resistivity (Ω-cm)

t = the sample thickness (cm)

k = a correction factor* based on the ratio of the probe spacing to wafer diameter and on the ratio of wafer thickness to probe spacing

* The correction factors can be found in a standard four-point probe resistivity test procedure such as *Semi MF84: Standard Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe.* This standard was originally published by ASTM International as ASTM F 84.

Using the Four-Point Probe Tests

The *Solar Cell High Resistance* or "*hir*" test or the *Solar Cell Low Resistance* or "*lor*" tests are both used for making four-point collinear probe measurements. The "*hir*" test can be used for materials over a wide resistance range, ~1 mΩ to 1 TΩ. The 4200-PA preamps are required for making high resistance measurements (>1MΩ). The "*lor*" test is intended for measurements of lower resistance materials (~1 mΩ–1 kΩ).

A screenshot of the "*hir*" test for measuring four-probe resistivity is shown in **Figure 19**.

The *Solar Cell High Resistance* test (*hir*) uses either three or four SMUs to make the resistivity measurements. One SMU (SMU1) and the ground unit (GNDU) are used to source current between the outer two probes. Two other SMUs (SMU2 and SMU3) are used to measure the voltage drop between the two inner probes. The Force HI terminal of each SMU is connected to each of the four probes. The SMU designation for this configuration is shown in **Figure 20**.

In the Formulator, the voltage difference between SMU2 and SMU3 is calculated and the resistance and sheet resistivity are derived from the voltage difference. The results appear in the Sheet in the Analyze pane of the test.

When making high resistance measurements, potential sources of error need to be considered in order to make optimal measurements. Use a probe head that has a level of insulation resistance between the probes that is sufficiently higher than the resistance of the material to be measured. This will help prevent errors due to leakage current through the probe head. Ensure that the measurement circuit is electrostatically shielded by enclosing the circuit in a metal shield. The shield is connected to the LO terminal of the 4200A. The LO terminal is located on the GNDU or on the outside shell of the triax connectors. Use triax cables to produce a guarded measurement circuit. This will prevent

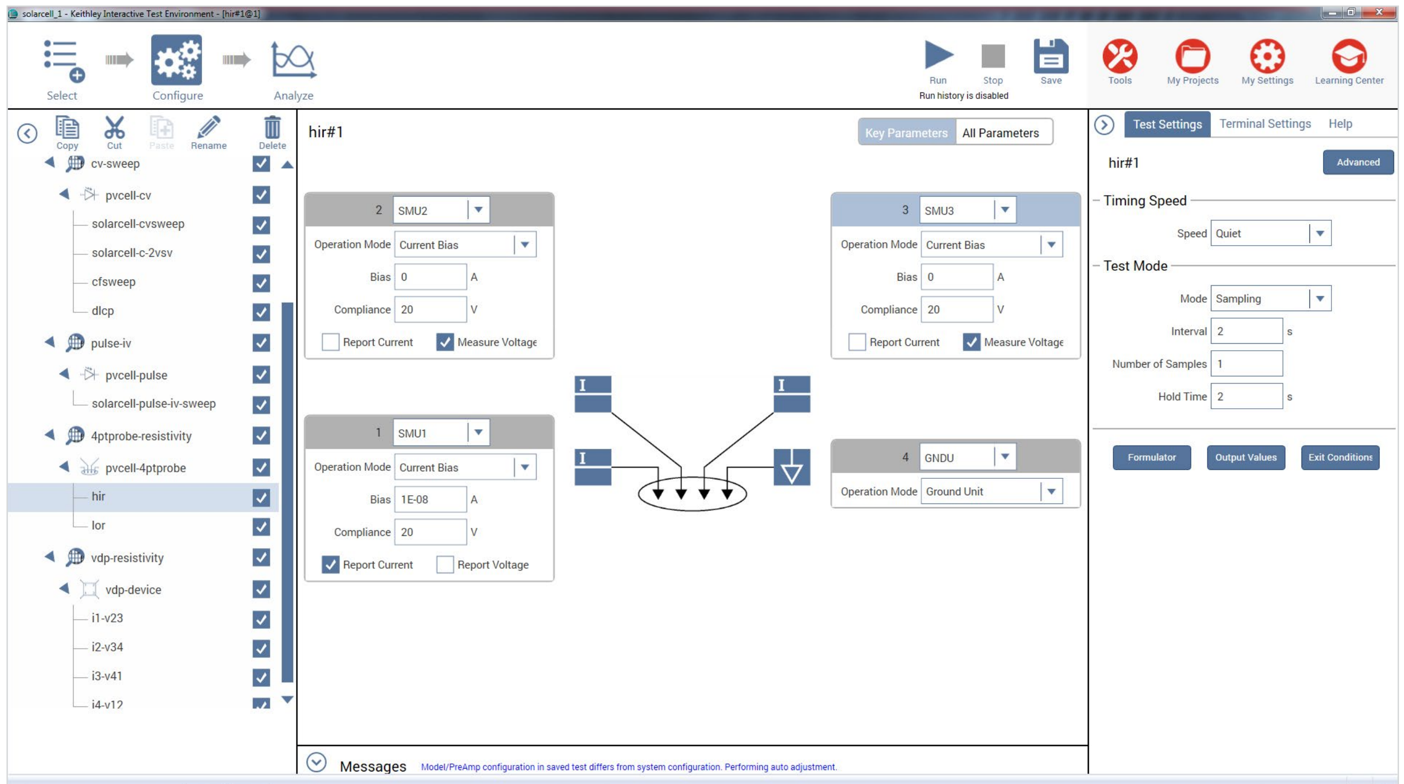

Figure 19. “hir” test module for measuring resistivity

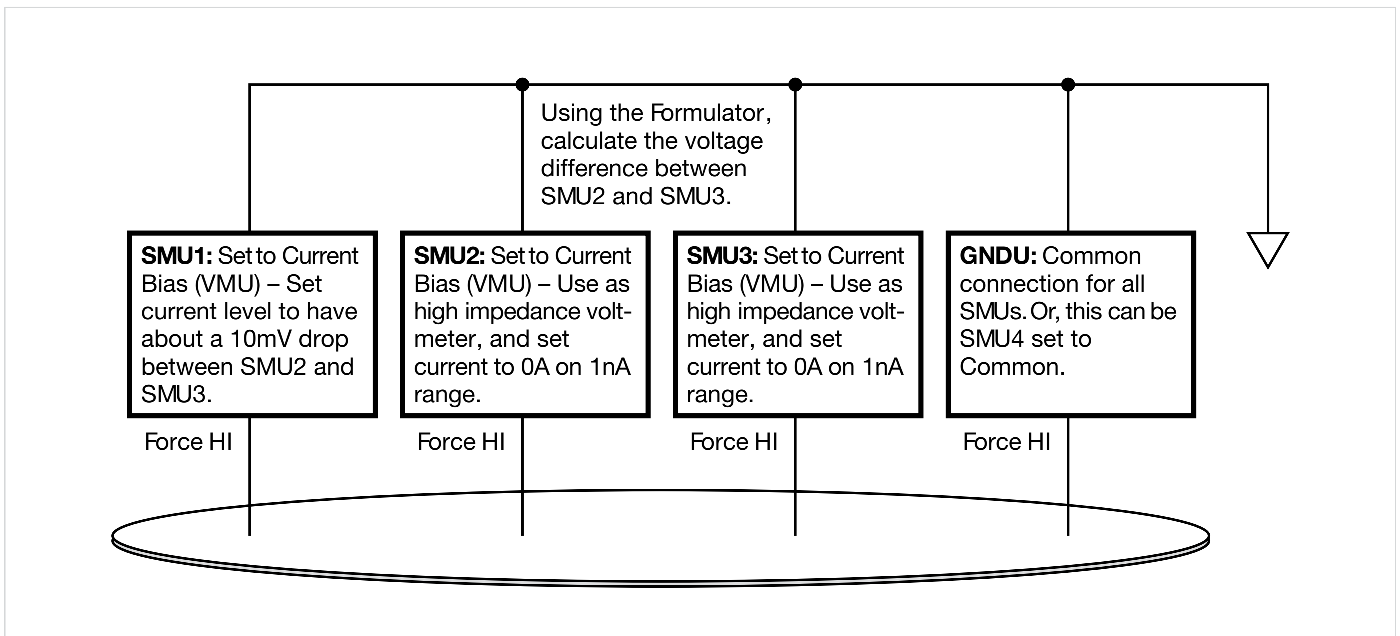

Figure 20. SMU designation for four-point collinear probe measurements

errors due to leakage current and significantly reduce the test time. Finally, the 4200-PA preamp option is required to source very small currents (nanoamp and picoamp range) and to provide high input impedance (>1E16 ohms) to avoid loading errors when measuring the voltage difference.

The *Solar Cell Low Resistance* (*lor*) test is only used for lower resistance materials and requires only one or two SMUs. In this case, the Force and Sense terminals of the SMUs are connected to the four-point probe as shown in **Figure 20**.

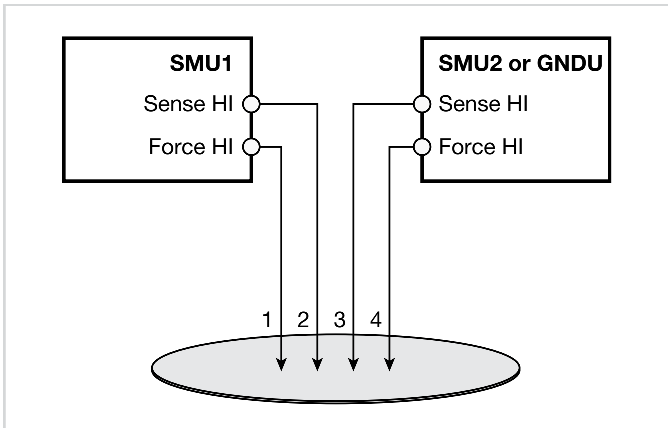

Figure 21. Connecting two SMUs for four-point probe measurements

In the configuration shown in **Figure 21**, the Force HI terminal SMU1 sources the current through Probe 1. The voltage difference between Probes 2 and 3 is measured through the Sense terminals of the two SMUs.

To compensate for thermoelectric offset voltages, two voltage measurements are made with currents of opposite polarity. The two measurements are combined and averaged to cancel the thermoelectric EMFs. The *Solar Cell Low Resistance* (*lor*) test performs this offset correction automatically by sourcing the two current values in the List Sweep and then mathematically correcting for the offsets in the Formulator. The corrected resistance and sheet resistivity are displayed in the Sheet.

Measuring Resistivity with the van der Pauw Method

The van der Pauw (vdp) technique for measuring resistivity uses four isolated contacts on the boundary of a flat, arbitrarily shaped sample. The resistivity is derived from eight measurements made around the sample as shown in **Figure 22**.

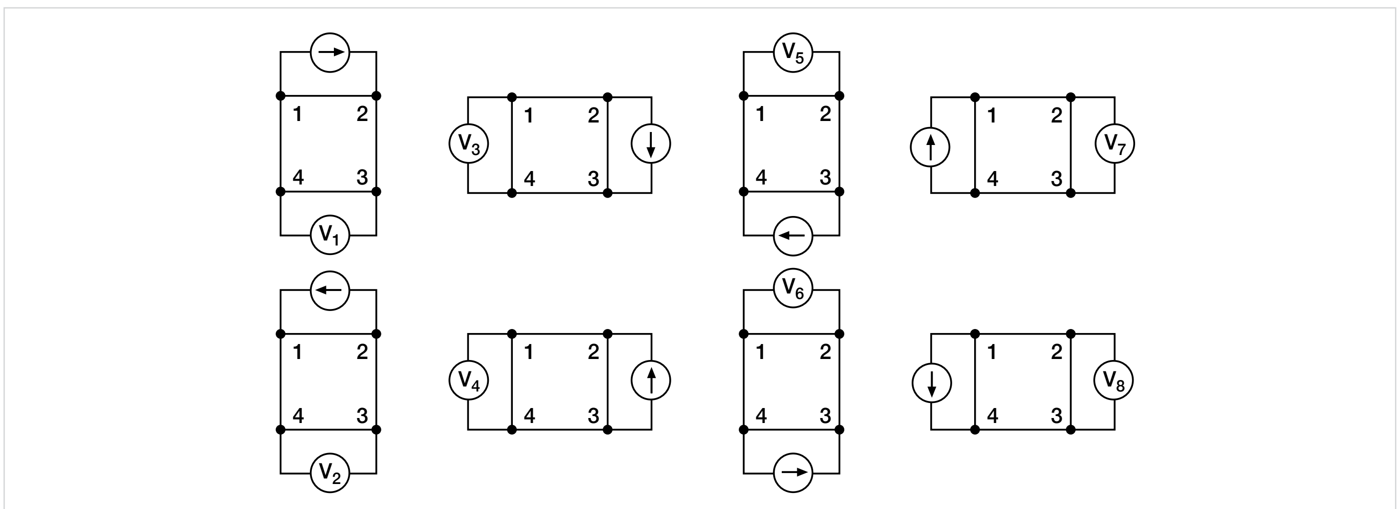

Figure 22. van der Pauw resistivity measurement conventions

Once all the voltage measurements have been taken, two values of resistivity, ρ_A and ρ_B, are derived as follows:

$$\rho_A = \frac{p}{ln^2} f_A t_s \frac{(V_2 + V_4 - V_1 - V_3)}{4I}$$

$$\rho_B = \frac{p}{ln^2} f_B t_s \frac{(V_6 + V_8 - V_5 - V_7)}{4I}$$

where:

ρ_A and ρ_B are volume resistivities in ohm-cm;

t_s is the sample thickness in cm;

V_1–V_8 represent the voltages measured by the voltmeter;

I is the current through the sample in amperes;

f_A and f_B are geometrical factors based on sample symmetry, and are related to the two resistance ratios Q_A and Q_B as shown in the following equations ($f_A = f_B = 1$ for perfect symmetry).

Q_A and Q_B are calculated using the measured voltages as follows:

$$Q_A = \frac{V_2 - V_1}{V_4 - V_3}$$

$$Q_B = \frac{V_6 - V_5}{V_8 - V_7}$$

Also, Q and f are related as follows:

$$\frac{Q - 1}{Q + 1} = \frac{f}{0.693} \text{arc cosh} \left(\frac{e^{0.693/f}}{2} \right)$$

A plot of this function is shown in **Figure 23**. The value of “f” can be found from this plot once Q has been calculated.

Once ρ_A and ρ_B are known, the average resistivity (ρ_{AVG}) can be determined as follows:

$$\rho_{AVG} = \frac{\rho_A + \rho_B}{2}$$

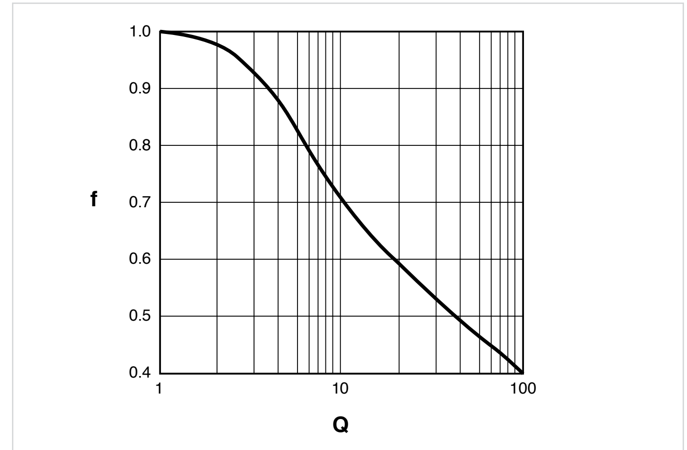

Figure 23. Plot of f vs. Q

Using the *vdp-resistivity* subsite and vdp method tests

To automate the vdp resistivity measurements, the *solarcell* project has a *vdp-resistivity* subsite with four tests: “*i1-v23*”, “*i2-v34*”, “*i3-v41*”, and “*i4-v12*.” A screenshot of the test is shown in **Figure 24**.

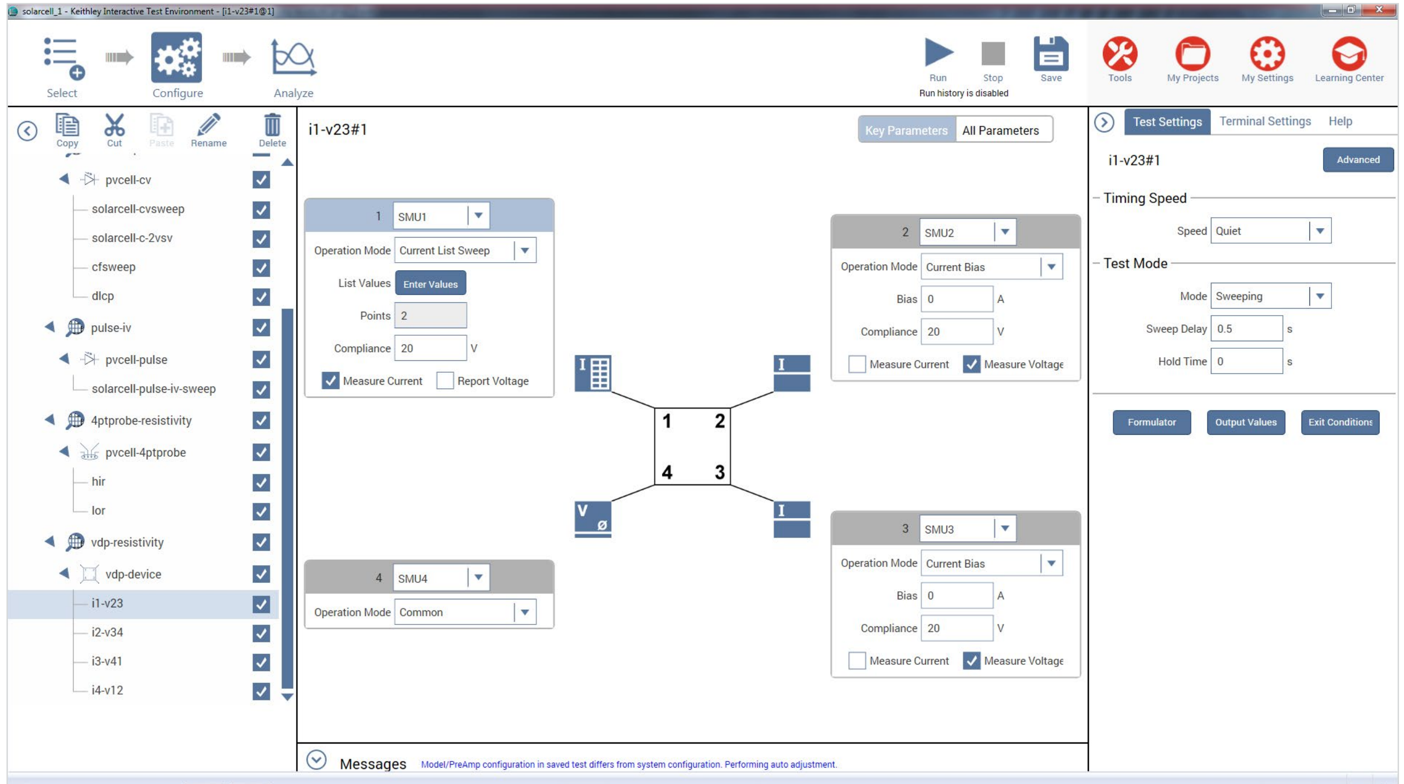

Figure 24. Screenshot of van der Pauw test

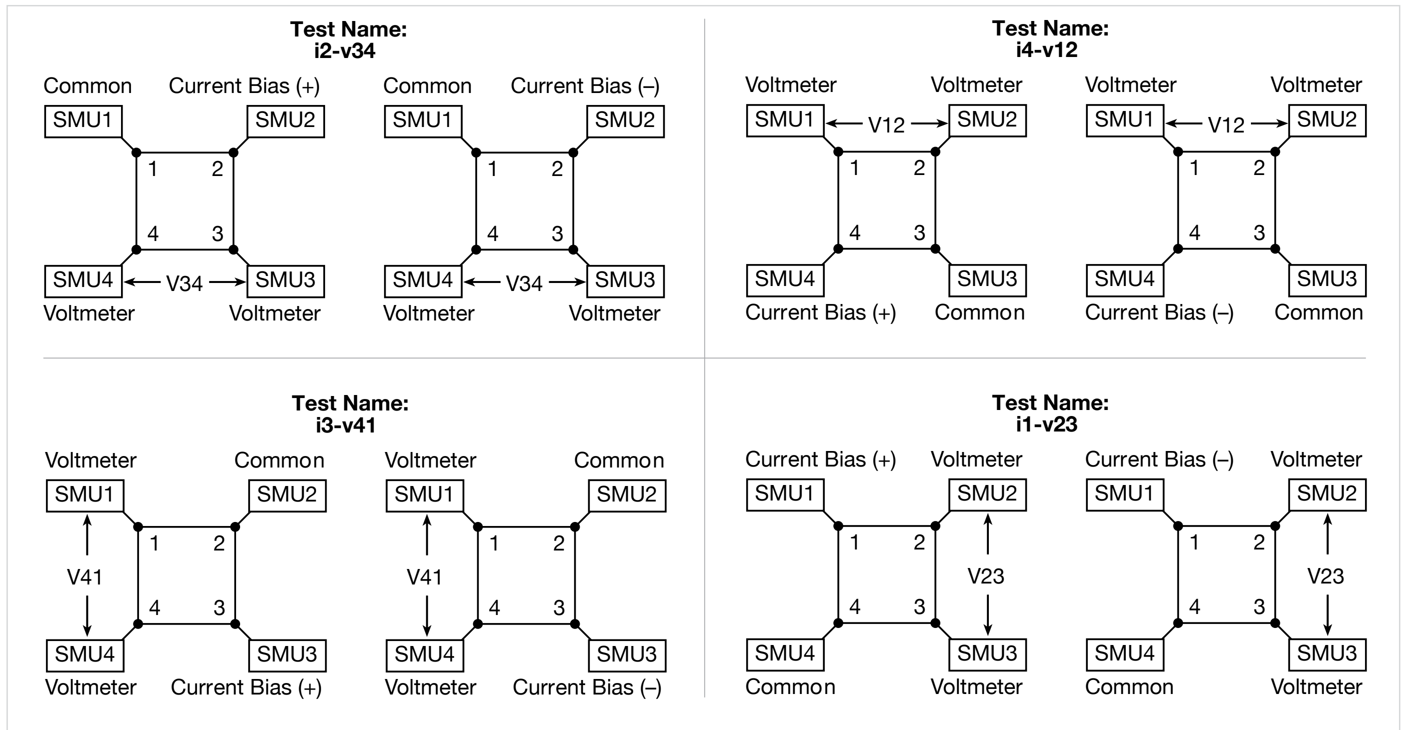

Figure 25. SMU configurations for van der Pauw measurements

Each terminal of the sample is connected to the Force HI terminal of an SMU, so a 4200A-SCS with four SMUs is required. The four SMUs are configured differently in each of the four tests – one SMU supplies the test current, two are configured as voltmeters, and one is set to common. This measurement setup is repeated around the sample, with each of the four SMUs serving a different function in each of the four tests. A diagram of the function of each SMU in each test is shown in **Figure 25**.

Adjusting the Test Parameters

Before executing the test, some of the test parameters must be adjusted based on the sample to be tested. In particular, it's necessary to specify the source current, the settling time, and the thickness of the material.

Input Source Current: Before running the project, input the current source values based on the expected sample resistance. Adjust the current so that the voltage difference will not exceed approximately 25 mV to keep the sample in thermal equilibrium. In each of the four tests, enter both polarities of the test current. The same magnitude must be used for each test.

Input the Settling Time: For high resistance samples, it will be necessary to determine the settling time of the measurements. This can be accomplished by creating a test that sources current into two terminals of the samples and measures the voltage drop on the adjacent two terminals. The settling time can be determined by taking multiple voltage readings and then graphing the voltage difference as a function of time.

This settling time test can be generated by copying and then modifying one of the existing vdp tests. Switch the source function from the sweep mode to the sampling mode. Then, in the Test Settings pane, take a few hundred or so readings with a delay time of one second. Make sure that the "Report Timestamps" box is selected. After the readings are done, plot the voltage difference vs. time on the graph. The settling time is determined by observing the graph and finding the time when the reading is within the desired percentage of the final value.

Input the Thickness of the Sample: Enter the thickness of the sample into the Calc sheet at the subsite level. Select the subsite vdp_resistivity. Go to the Subsite Data vdp-device tab. It contains the output values of the voltage differences and test current. From the Calc tab, the thickness can be adjusted. The default thickness is 1 cm.

Input Correction Factor: The resistivity formula found in the Calc sheet at the subsite level also allows inputting a correction factor, if necessary. The resistivity is multiplied by this number, which may be based on the geometry or uniformity of the sample. By default, the correction factor is 1.

Running the Project

The van der Pauw resistivity measurements must be run at the subsite level. Make sure that all four checkboxes to the right of the vdp tests ("*i1-v23*," "*i2-v34*," "*i3-v41*," and "*i4-v12*") are selected and then select *vdp_resistivity*. Execute the project by using the Run button. Each time the test is run, the subsite data is updated. The voltage differences from each of the four tests will appear in the Subsite Data vdp-device Sheet tab. The resistivity will appear in the Subsite Data Calc sheet as shown in **Figure 26**.

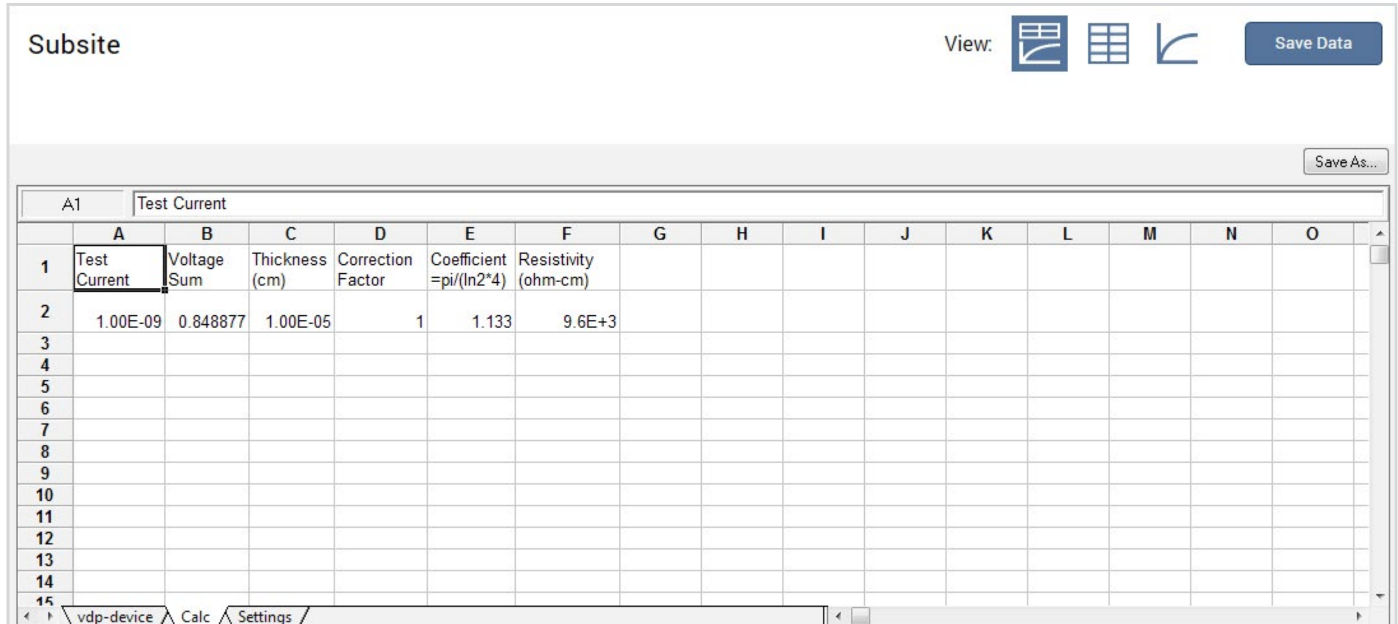

Figure 26. vdp resistivity calculation

Hall Voltage Measurements

Hall effect measurements are important to semiconductor material characterization because the conductivity type, carrier density, and Hall mobility can be derived from the Hall voltage. With an applied magnetic field, the Hall voltage can be measured using the configuration shown in **Figure 27**.

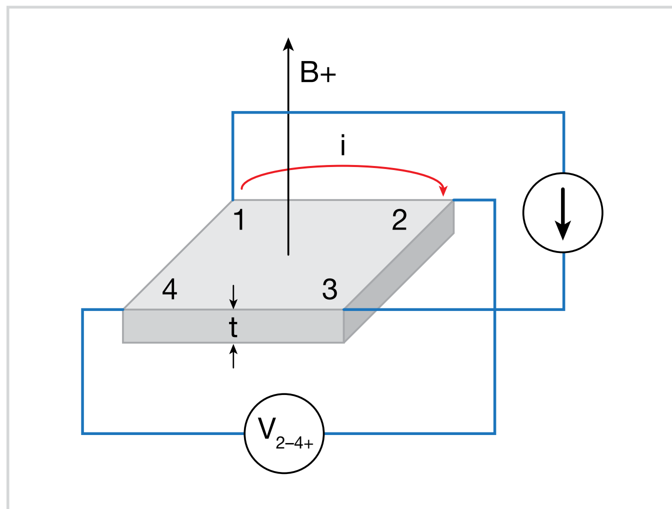

Figure 27. Hall voltage measurement

With a positive magnetic field (B+), apply a current between Terminals 1 and 3 of the sample, and measure the voltage drop (V_{2-4+}) between Terminals 2 and 4. Reverse the current and measure the voltage drop (V_{4-2+}). Next, apply current between Terminals 2 and 4, and measure the voltage drop (V_{1-3+}) between Terminals 1 and 3. Reverse the current and measure the voltage drop (V_{3-1}+) again.

Reverse the magnetic field (B–) and repeat the procedure, measuring the four voltages: (V_{2-4-}), (V_{4-2-}), (V_{1-3-}), and (V_{3-1-}). **Table 3** summarizes the Hall voltage measurements.

Table 3. Summary of Hall Voltage Measurements

Voltage Designation	Magnetic Flux	Current Forced Between Terminals	Voltage Measured Between Terminals
V2–4+	B+	1–3	2–4
V4–2+	B+	3–1	4–2
V1–3+	B+	2–4	1–3
V3–1+	B+	4–2	3–1
V2–4–	B–	1–3	2–4
V4–2–	B–	3–1	4–2
V1–3–	B–	2–4	1–3
V3–1–	B–	4–2	3–1

From the eight Hall voltage measurements, the average Hall coefficient can be calculated as follows:

$$R_{HC} = \frac{t(V_{4-2+} - V_{2-4+} + V_{2-4-} - V_{4-2-})}{4BI}$$

$$R_{HD} = \frac{t(V_{3-1+} - V_{1-3+} + V_{1-3-} - V_{3-1-})}{4BI}$$

where:

R_{HC} and R_{HD} are Hall coefficients in cm^3/C;

t is the sample thickness in cm;

V represents the voltages measured in V;

I is the current through the sample in A;

B is the magnetic flux in Vs/cm^2

Once R_{HC} and R_{HD} have been calculated, the average Hall coefficient (R_{HAVG}) can be determined as follows:

$$R_{HAVG} = \frac{R_{HC} + R_{HD}}{2}$$

From the resistivity (ρ_{AVG}) and the Hall coefficient (R_H), the Hall mobility (μ_H) can be calculated:

$$\mu_H = \frac{|R_H|}{\rho_{AVG}}$$

Using the 4200A-SCS to Measure the Hall Voltage

The *SolarCell* project does not include a specific test to measure the Hall voltage; however, four tests can be added to the subsite for determining the Hall coefficient and mobility. Given that the configuration for the Hall measurements is very similar to the van der Pauw resistivity measurements, the vdp tests can be copied and modified for making the Hall voltage measurements. The modifications involve changing the functions of the SMUs. **Figure 28** illustrates how to configure the four SMUs in the tests to measure the Hall voltage. Use the Output Value checkboxes on the Test Settings pane of each test to return the Hall voltages to the subsite-level Calc sheet.

A custom test must be added to control the magnet. For a GPIB-controlled electromagnet, users can write a user module using KULT (the Keithley User Library Tool) to control the magnitude and polarity of the electromagnet. The code can be opened up in a custom test within the project. Information on writing code using KULT is provided in the 4200A-SCS Reference Manual.

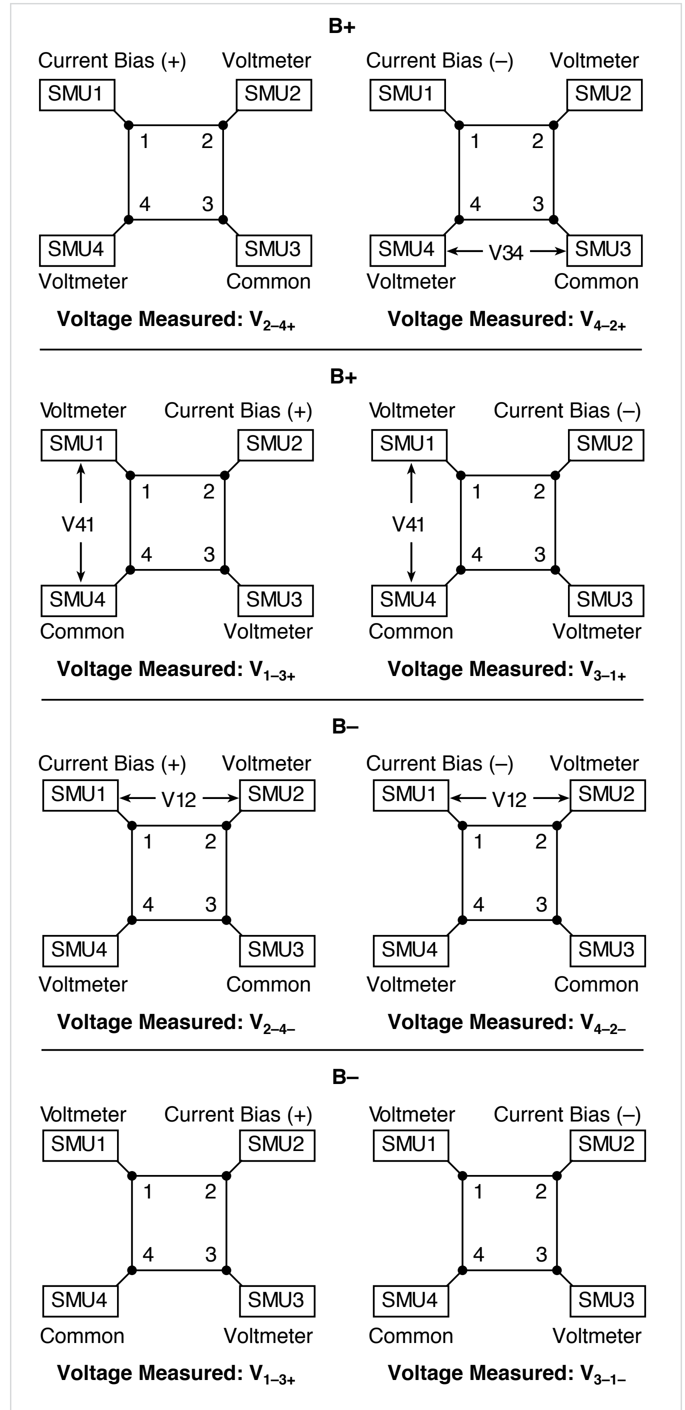

Figure 28. SMU configurations for Hall voltage measurements

If a permanent magnet is used, an Action from the Actions Library can be used to create a dialog box Project Prompt that will stop the test sequence in the project tree and instruct the user to change the polarity of the magnetic field applied to the sample. A Project Prompt is a dialog window that pauses the project test sequence and prompts the user to perform some action. See the 4200A-SCS Reference Manual for a description of how to use Dialog Box Actions.

Finally, the Hall coefficient and mobility can be derived in the subsite-level Calc sheet. These math functions can be added to the other equations for determining resistivity.

Instead of using four separate tests and the subsite-level Calc Sheet for making Hall voltage measurements, add the hall-coefficient test from the Library, which combines all the measurements and parameter extractions into one test.

Conclusion

Measuring the electrical characteristics of a solar cell is critical for determining the device's output performance and efficiency. The 4200A-SCS simplifies cell testing by automating the I-V, C-V, pulsed I-V, and resistivity measurements and provides graphics and analysis capability. For measurements of currents greater than 1 A, Keithley offers SourceMeter instruments that can be used for solar cell testing. Information on these models and further information on making solar cell measurements can be found on Keithley's website: www.keithley.com.

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