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Application Note Series

Number 3224

I-V Characterization of Photovoltaic Cells Using the Model 2450 SourceMeter® Source Measure Unit (SMU) Instrument

Introduction

Solar or photovoltaic (PV) cells are devices that absorb photons from a light source and then release electrons, causing an electric current to flow when the cell is connected to a load. Researchers and manufacturers of PV cells strive to achieve the highest possible efficiency with minimal losses. As a result, electrical characterization of the cell as well as PV materials is performed as part of research and development and during the manufacturing process. The current-voltage (I-V) characterization of the cell is performed to derive important parameters about the cell's performance, including its maximum current (I_{max}) and voltage (V_{max}), open circuit voltage (V_{oc}), short circuit current (I_{sc}), and its efficiency (η).

These I-V characteristics can easily be generated using a Keithley Model 2450 SourceMeter SMU Instrument, which can source and measure both current and voltage. Because the Model 2450 has four-quadrant source capability, it can sink up to 1.05A @ 21V of cell current as a function of the applied voltage. This application note explains how to simplify I-V characterization of solar cells by using the Model 2450 SourceMeter SMU Instrument, shown in ***Figure 1***. In particular, this application note explains how to perform I-V testing from the front panel, including how to generate graphs and save the data to a USB drive. It also details how to automate the measurements over the bus.

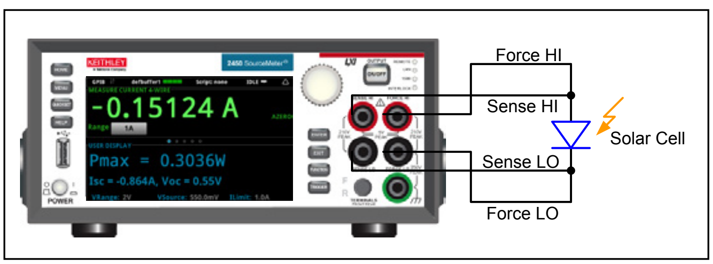


Figure 1. Model 2450 SourceMeter connections to a solar cell.

The Solar Cell

The 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 zero ohms. 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.

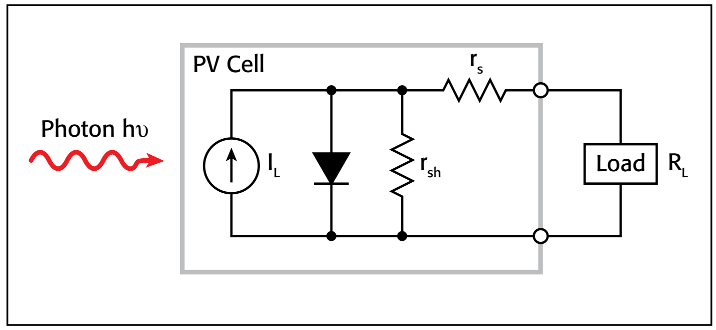


Figure 2. Idealized equivalent circuit of a photovoltaic cell.

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 short circuit current (I_{sc}), and the open circuit voltage (V_{oc}). These points are illustrated in ***Figure 3***, which shows a typical forward bias I-V curve of an illuminated solar 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.

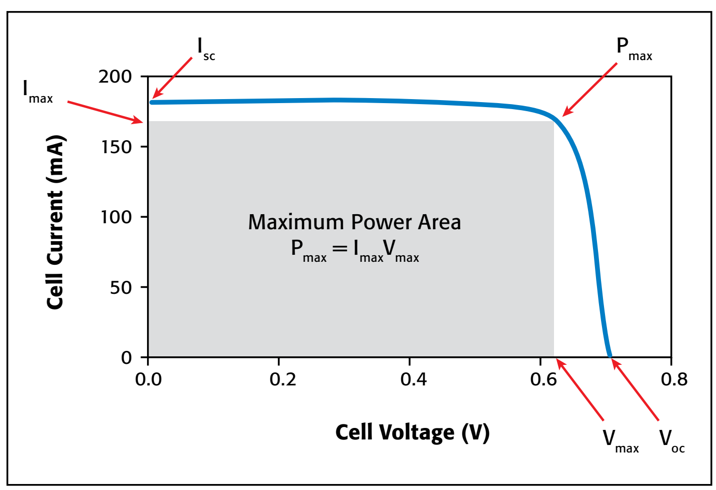
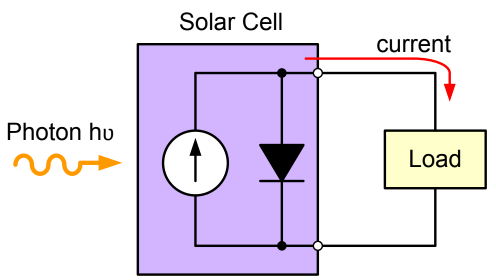


Figure 3. Typical forward bias I-V characteristics of solar cell.

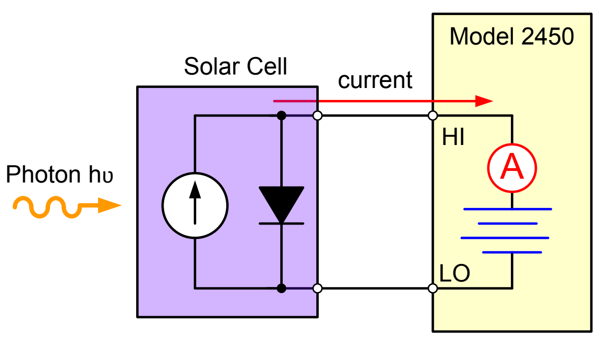
The Model 2450 as an Electronic Load

As illustrated in ***Figure 4***, when a load is connected to the output of an illuminated solar cell, a current will flow.

When the illuminated PV cell is connected to the output terminals of the Model 2450, the SourceMeter SMU instrument will sink the current. In other words, the Model 2450 becomes the load. As a result, the measured current is negative.



An illuminated solar cell will cause a current to flow when a load is connected to its terminals.



An illuminated solar cell will cause current to flow into the output terminals of the Model 2450 SourceMeter SMU Instrument, which acts as an electronic load and sinks the current. As a result, the measured current will be negative.

Figure 4. Model 2450 acts as an electronic load when connected to an illuminated PV cell.

Making Connections from the Model 2450 to a Solar Cell

The solar cell is connected to the Model 2450 as shown in ***Figure 5***. A four-wire connection is made to eliminate the effects of the lead resistance. When connecting the leads to the solar cell, notice that the Force LO and Sense LO connections are made to the cathode terminal. The Force HI and Sense HI connections are made to the anode. Make the connections as close as possible to the cell to prevent the resistance of the solar cell's terminals from affecting the measurement accuracy.

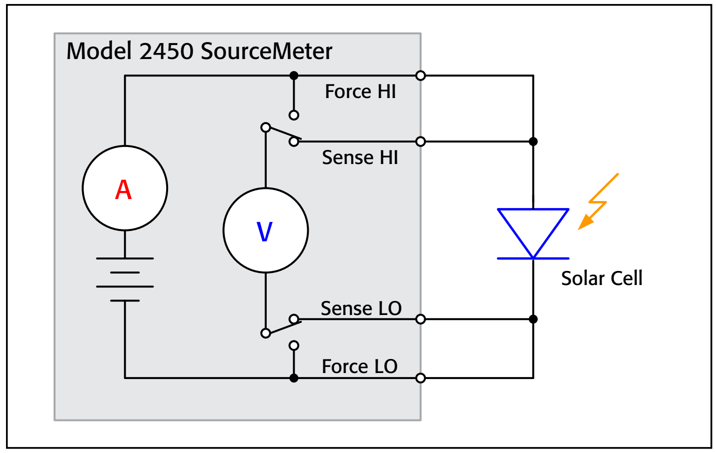


Figure 5. Connections of the Model 2450 to a solar cell.

Generating, Plotting, and Saving I-V Sweeps Using the User Interface in Three Easy Steps

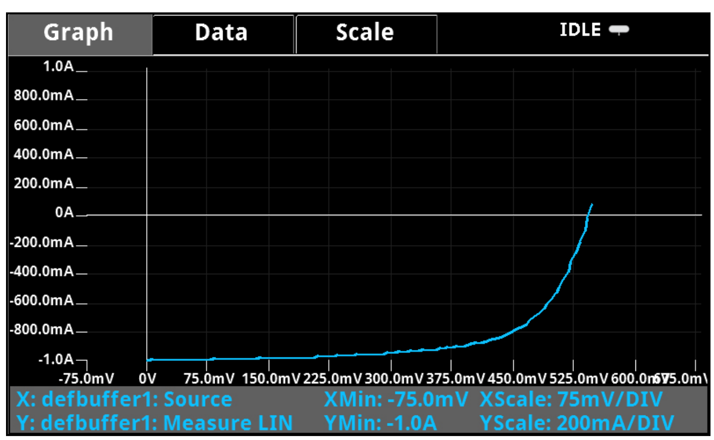
The I-V sweep of a PV cell can be accomplished from either the front panel or over the bus. Just a few key strokes are needed to generate, graph, and save the data to a USB drive. Here are the three easy steps to generate and graph a voltage sweep and then save the data to a USB drive.

Step 1. Creating and Executing an I-V Sweep

Description	**Key Strokes**
Reset instrument to default state	Menu key → Manage System → Reset
Set to source V and measure I	Home key → Function key → Source V Measure I
Set to four-wire sense	Menu key → Measure Settings → Sense Mode → 4-Wire Sense
Configure sweep parameters	Menu key → Source Sweep • Set desired Start, Stop, and Step V • Scroll down and set Source Limit • Press Generate to create sweep
Execute I-V sweep	Home key → Trigger key

Step 2. Viewing the Graph

To view the data graphically, press the MENU key and then the Graph button. The graph of the I-V sweep will automatically be displayed. To repeat the graph, just press the TRIGGER key.



Step 3. Saving the Data to a USB Drive

To save the I-V data to a USB drive, just insert a USB drive, press the MENU key, select Data Buffers, press the desired buffer, and then SAVE TO USB. Enter the name of the file. The data will be saved in a .csv format so it can later be downloaded to a spreadsheet and analyzed.

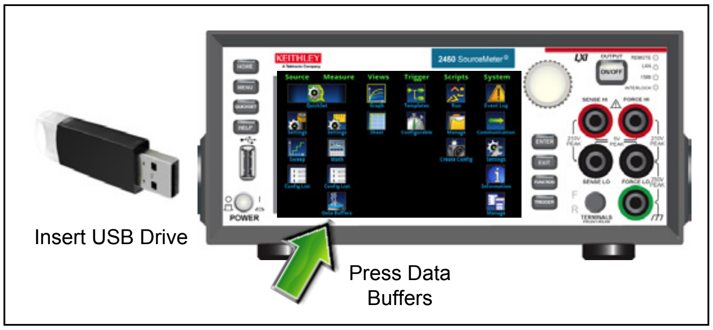


Figure 6. Saving data to a USB drive.

Automating I-V Measurements with Remote Programming

The Model 2450 can be remotely controlled by using either SCPI or TSP® commands with the flexibility of a LAN, USB, or GPIB interface. An example of how to program the Model 2450 to automate I-V characteristics on a PV cell was performed using a polycrystalline silicon solar cell. For this particular test, the Model 2450 was programmed to sweep voltage from 0V to 0.55V in 56 steps and to measure the resulting current in a four-wire configuration. The TSP code to perform this test is listed in Appendix A and the SCPI code is listed in Appendix B. The results of graphing the I-V characteristics of this cell are shown in the graph of ***Figure*** *7*. Notice the test on the solar cell was executed with light (Light ON) and in the dark (Light OFF). As previously discussed, the current in the "Light ON" graph is negative because the Model 2450 is sinking current. If desired, the curve can easily be inverted in the spreadsheet.

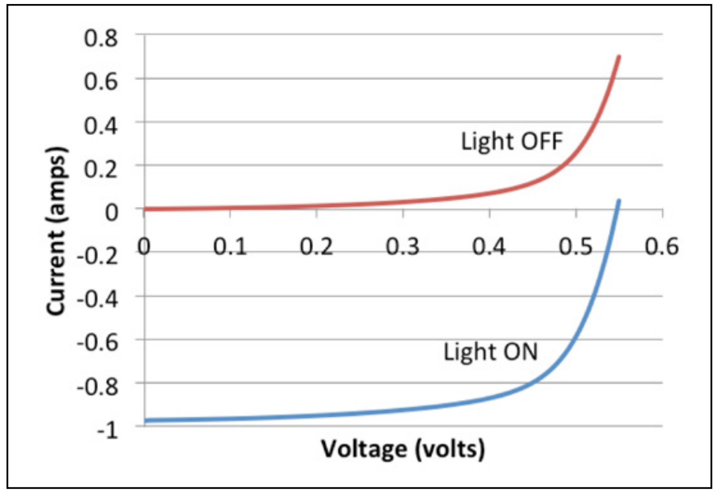


Figure 7. Solar cell I-V sweeps generated by Model 2450.

In addition to automating the I-V measurements over the bus, the Model 2450 can display the derived maximum power (P_{max}), short circuit current (I_{sc}), open circuit voltage (V_{oc}), or other user-derived calculations on its user interface. Notice the large, easy-to-read parameters of the solar cell on the Model 2450 display that is shown in the screen capture in ***Figure 8***.

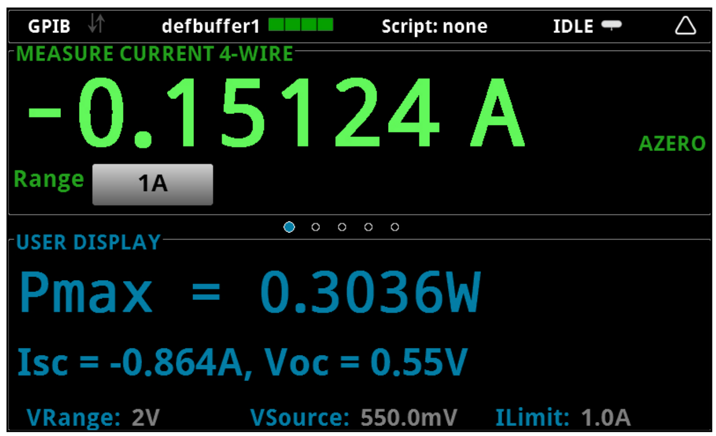


Figure 8. The Model 2450 display indicated maximum power (P_{max}), short circuit current (I_{sc}), and open circuit voltage (V_{oc}).

Appendix A: Example TSP Code

The following example TSP code is designed to be run from Keithley Instruments' Test Script Builder (TSB). TSB is a software tool included with the Model 2450. To use other programming environments, you will need to change the example TSP code. In this particular example, the voltage is swept from 0V to 0.55V in 56 steps, and the resulting current is measured. The current and voltage readings are stored in the default buffer, defbuffer1.

```
--Define number of points in sweep
num = 56

--Reset the instrument and clear the buffer
reset()

--Set source and measure functions
smu.measure.func = smu.FUNC_DC_CURRENT
smu.source.func = smu.FUNC_DC_VOLTAGE

--Measurement Settings
smu.measure.terminals = smu.TERMINALS_FRONT
smu.measure.sense = smu.SENSE_4WIRE
smu.measure.autorange = smu.ON
smu.measure.nplc = 1

--Source Settings
smu.source.highc = smu.OFF
smu.source.range = 2
smu.source.readback = smu.ON
smu.source.ilimit.level = 1
smu.source.sweeplinear('SolarCell', 0, 0.55, num, 0.1)

--Start the trigger model and wait for it to complete
trigger.model.initiate()
waitcomplete()

--Define initial values
voltage = defbuffer1.sourcevalues
current = defbuffer1
isc = current[1]
mincurr = current[1]
imax = current[1]
voc = voltage[1]
vmax = voltage[1]
pmax = voltage[1]*current[1]

--Calculate values
for i = 1, num do
      print(voltage[i],current[i],voltage[i]*current[i])
      if (voltage[i]*current[i] < pmax) then
            pmax = voltage[i]*current[i]
            imax = current[i]
            vmax = voltage[i]
      end
      if math.abs(current[i]) < math.abs(mincurr) then
            voc = voltage[i]
```

```
        end
    end

    pmax = math.abs(pmax)
    imax = math.abs(imax)

    print("Pmax = ", pmax, ", Imax = ", imax, ", Vmax = ", vmax, ", Isc = ", isc, ", Voc = ", voc)

    --Display values on 2450 front panel
    display.changescreen(display.SCREEN_USER_SWIPE)
    display.settext(0, string.format("Pmax = %.4fW", pmax))
    display.settext(1, string.format("Isc = %.4fA, Voc = %.2fV", isc, voc))
```

Appendix B: Example SCPI Code

The example sequence of SCPI commands is designed to generate an I-V sweep on a solar cell. You must make the appropriate changes so it will run in your programming environment. In this particular example, the voltage is swept from 0V to 0.55V in 56 steps and the resulting PV cell current is measured. The current and voltage readings are stored in the buffer, defbuffer1.

Sequence of SCPI Commands	Description
`*RST`	Reset
`SENS:FUNC "CURR"`	Measure current
`SENS:CURR:RANG:AUTO ON`	Autorange
`SENS:CURR:RSEN ON`	4-wire sense mode
`SOUR:FUNC VOLT`	Source voltage
`SOUR:VOLT:RANG 2`	2 V source range
`SOUR:VOLT:ILIM 1`	1 A current limit
`SOUR:SWE:VOLT:LIN 0, 0.55, 56, 0.1`	Sweep voltage from 0 to 0.55V in 56 steps at 100ms intervals
`:INIT`	Initiate sweep
`*WAI`	Wait until sweep is finished
`TRAC:DATA? 1, 56, "defbuffer1", SOUR, READ`	Read source and measure values from buffer

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Printed in the U.S.A No. 3224 7.12.13