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Making I-V and C-V Measurements on Solar/Photovoltaic Cells Using the Model 4200-SCS Semiconductor Characterization System

Introduction

Because of the increasing demand for energy and the limited supply of fossil fuels, the search for alternative sources of power is imperative. Given that there is a vast amount of energy available from the sun, devices that convert light energy into electrical energy are becoming increasingly important. Solar or photovoltaic (PV) cells convert light energy into useful electrical power. These cells are produced from light-absorbing materials. When the cell is illuminated, optically generated carriers produce an electric current when the cell is connected to a load.

A variety of measurements are made to determine the electrical characteristics of PV cells. Characterizing the cells often involves measuring the current and capacitance as a function of an applied DC voltage. The measurements are usually done at different light intensities and temperature conditions. Important device parameters can be extracted from the current-voltage (I-V) and capacitance-voltage (C-V) measurements, such as the conversion efficiency and the maximum power output. Electrical characterization is also important to determine losses in the PV cell. Essentially, electrical characterization is needed to determine ways to make the cells as efficient as possible with minimal losses.

To make these important electrical measurements, using a tool such as the Model 4200-SCS Semiconductor Characterization System can simplify testing and analysis. The 4200-SCS is a measurement system that includes instruments for both I-V and C-V measurements, as well as software, graphics, and mathematical analysis capability. The software includes tests for making I-V and C-V measurements specifically on solar cells and deriving common PV cell parameters from the test data. This application note describes how to use the Model 4200-SCS to make electrical measurements on PV Cells. Topics include the basic principles of PV cells, connections of the cell in the measurement circuits, forward and reverse I-V measurements, C-V measurements, measurement considerations, and sources of error.

Basic Photovoltaic Cell Circuit and Device Parameters

A photovoltaic cell may be represented by the equivalent circuit model shown in ***Figure 1***. This model consists of current due to optical generation (I_L), a diode that generates a current [$I_s(e^{qV/kT})$], a 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 short-circuit current and the maximum power output of the cell. Ideally, the series resistance should be 0Ω ($r_s = 0$). The shunt resistance represents the loss due to surface leakage along the edge of the cell or due to crystal defects. Ideally, the shunt resistance should be infinite ($r_{sh} = \infty$).

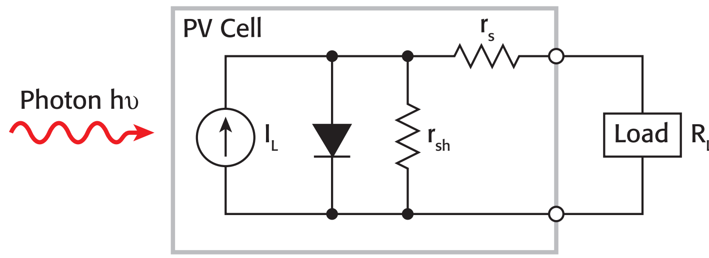

Figure 1. Idealized equivalent circuit of a photovoltaic cell

If a load resistor (R_L) is connected to an illuminated PV 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 factors determine 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 2***, 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 voltage (V_{max}) where the power output of the cell is greatest. This point is located at the "knee" of the curve.

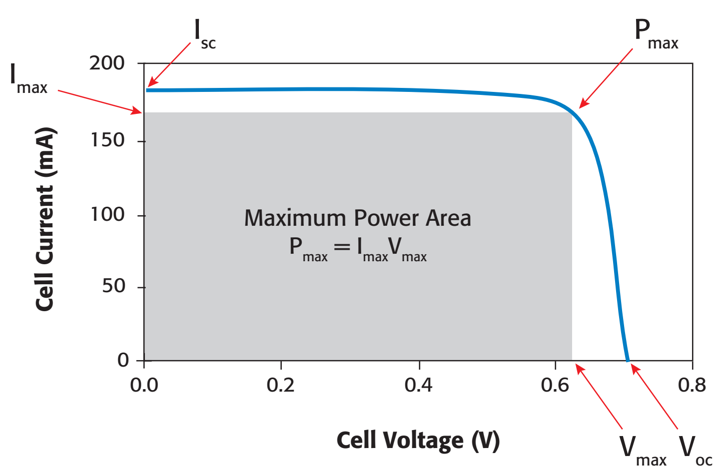

Figure 2. Typical forward bias I-V characteristics of a PV cell

The fill factor 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
V_{max} = the voltage at the maximum power output
I_{sc} = the short-circuit current
V_{oc} = the open-circuit voltage

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

These described parameters of the solar cell can be determined through electrical characterization of the device.

Using the 4200-SCS to Make I-V and C-V Measurements on the Solar Cell

To simplify testing, a project has been created for the 4200-SCS that makes both I-V and C-V measurements on a solar cell and also extracts common measurement parameters such as maximum power, short-circuit current, open-circuit voltage, etc. The project is called "CVU_Pvcell" and is included with all 4200-SCS systems running KITE version 7.0 or later. A screen shot of the project is shown in ***Figure 3***. This project has five tests, called ITMs (Interactive Test Modules), that perform a forward bias I-V sweep (*fwd-ivsweep*), reverse bias I-V sweep (*rev-ivsweep*), C-V sweep (*cvsweep*), 1/C² vs. V plot (*C-2vsV*) and C-f sweep (*cfsweep*).

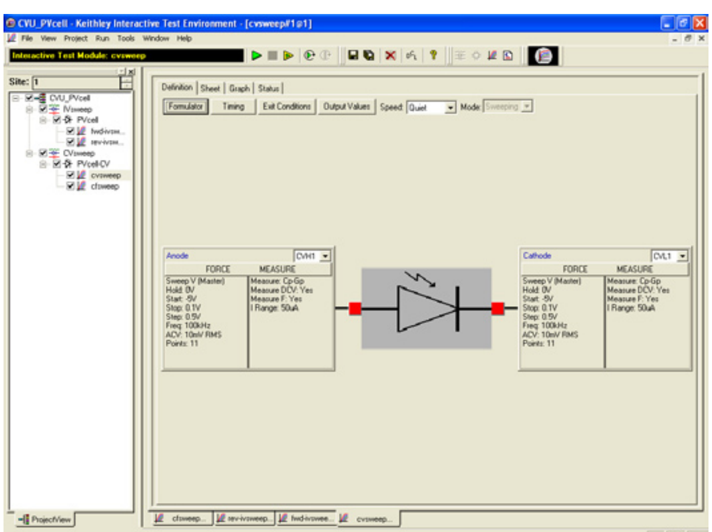

Figure 3. Screen Shot of PV Cell Project for the 4200

I-V Measurements Using the 4200-SMU

As described previously, many important device parameters can be determined from current-voltage (I-V) measurements of the solar cell. The I-V characteristics are measured using one of the Model 4200-SCS's Source Measure Units (SMUs), which can source and measure both current and voltage. Two types of SMUs are available for the 4200-SCS: the Model 4200-SMU, which can source/sink up to 100mA, and the 4210-SMU, which can source/sink up to 1A. If the output current of the cell exceeds these current levels, then the output current may have to be reduced. One way of reducing the output is to reduce the area of the cell. If this is not possible, then the Keithley Series 2400 SourceMeter® instruments, which are capable of sourcing/sinking higher currents, may be used.

Making connections to the PV Cell

A solar cell connected to the 4200-SCS's SMU for I-V measurements is shown in ***Figure 4***. A four-wire connection is made to eliminate the lead resistance that could otherwise affect the measurement accuracy. With the four-wire method, a voltage is sourced across the PV cell using one pair of leads (Force HI and Force LO), and the voltage drop across the cell is measured across a second set of leads (Sense HI and Sense LO). The sense leads ensure that the voltage developed across the cell is the programmed output value and compensates for the lead resistance.

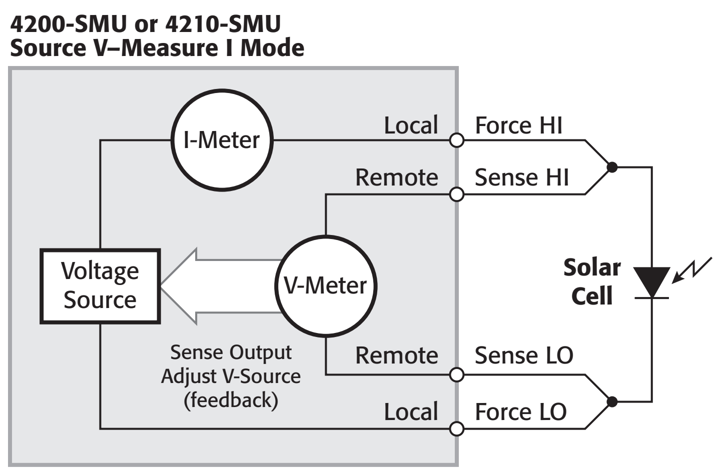

Figure 4. Connections of 4200-SCS's SMU to Solar Cell

Forward Bias I-V Measurements

Forward bias I-V measurements of the PV cell are generated under controlled illumination. The SMU is set up to source a voltage sweep and measure the resulting current. This forward bias sweep can be accomplished using the "*fwd-ivsweep*" ITM. The user can adjust the sweep voltage to the desired values. As illustrated in ***Figure 2***, 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 short-circuit current (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 easily be derived from the sweep data using the Model 4200-SCS's built-in mathematical analysis tool, the Formulator. For convenience, the "CVU_Pvcell" project has the common parameters already calculated and the values automatically appear in the Sheet tab every time the test is executed. ***Figure 5*** shows some of the derived parameters in the Sheet tab. 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).

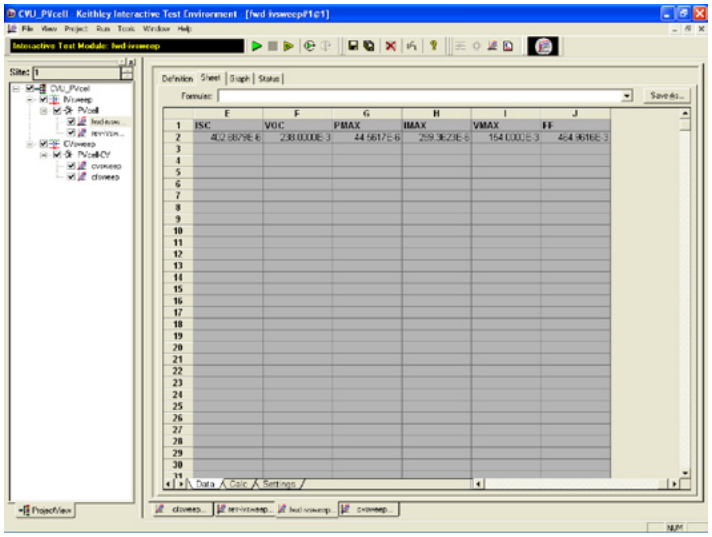

Figure 5. Results of Calculated Parameters Shown in Sheet Tab

Using the Formulator, the conversion efficiency (η) can also be calculated if the power input to the cell is known. The current density (J) can also be derived using the area of the cell.

Figure 6 shows an actual I-V sweep of an illuminated silicon PV cell generated by the 4200-SCS using the "*fwd-ivsweep*" ITM. Because the system's SMUs can sink current, the curve can pass through the fourth quadrant and allow power to be extracted from the device (I^-, V^+). Sometimes it may be desirable to plot log I vs. V. The Graph tab options support an easy transition between graphically displaying data on either a linear or a log scale.

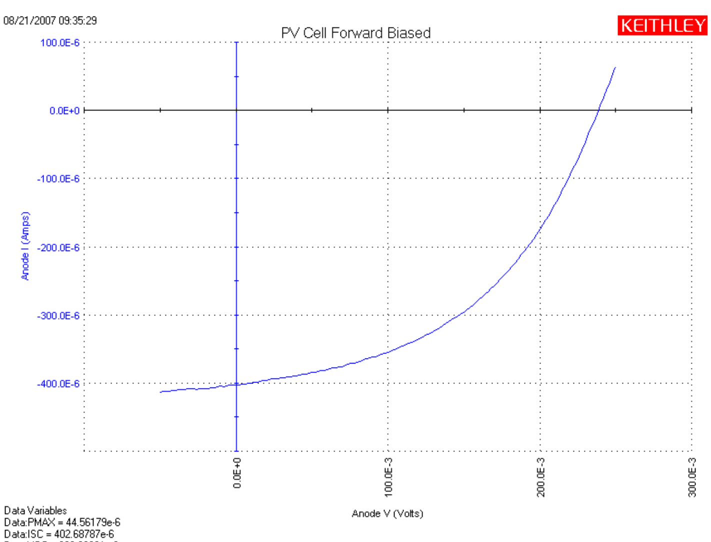

Figure 6. I-V Sweep of Silicon PV Cell Generated with the 4200-SMU

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. Knowing the magnitudes of the intensities is 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:

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

Using additional light intensities, this technique can be extended using multiple points located near the knee of the curves. As illustrated in ***Figure*** *7*, a line is generated from which the series resistance can be calculated from the slope.

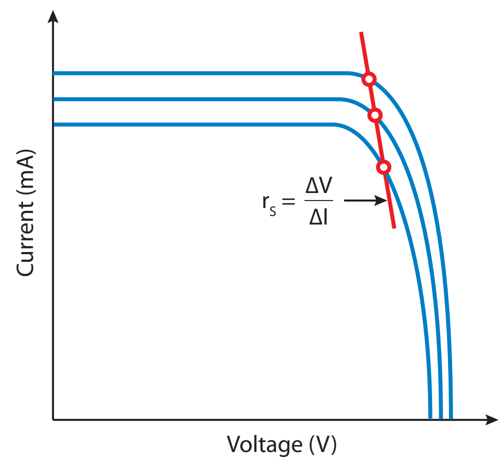

Figure 7. Slope Method Used to Calculate the Series Resistance

An important measurement feature of the system's SMU as an ammeter is that it has 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 200mV at full scale. Given that only millivolts may be sourced to the sample, this can cause large errors. The 4200-SCS's SMU never produces more than a few hundred microvolts of voltage burden, or voltage drop, in the measurement circuit.

Reverse Bias I-V Measurements

The leakage current and shunt resistance (r_{sh}) can be derived from the reverse bias 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 in the picoamp region. The Model 4200-SCS has a preamp option that allows making accurate measurements well below a picoamp. When making very sensitive low current measurements (nanoamps and smaller), use low noise cables and place the device in a shielded enclosure to shield the device electrostatically. This conductive shield is connected to the Force LO terminal of the 4200-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 bias I-V curve, as shown in ***Figure 8***. From the linear region of this curve, the shunt resistance can be calculated as:

$$r_s = \frac{\Delta V_{\text{Reverse Bias}}}{\Delta I_{\text{Reverse Bias}}}$$

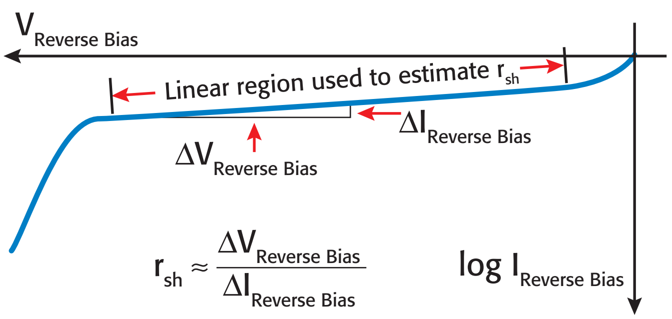

Figure 8. Typical Reverse-Bias Characteristics of a PV Cell

An actual curve of a reverse-biased PV cell is shown in ***Figure 9***. This curve was generated using the ITM "*rev-ivsweep*". In this semi-log graph, the absolute value of the current is plotted as a function of the reverse bias voltage that is on an inverted x-axis.

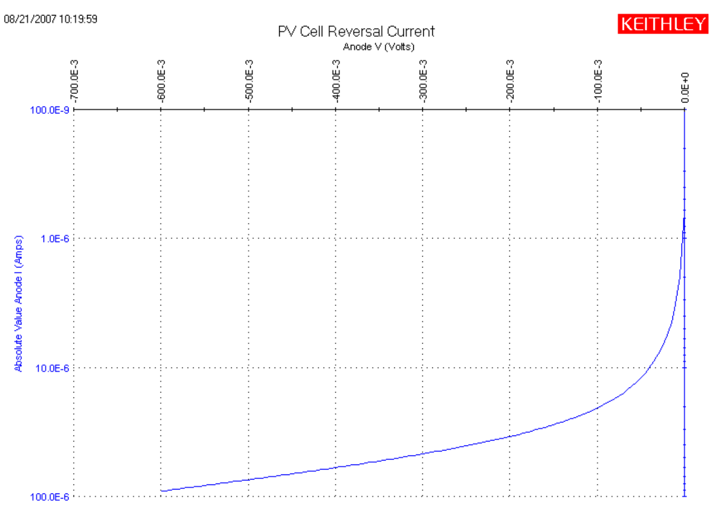

Figure 9. Actual Reverse Bias Measurement of Silicon PV Cell Using 4200-SMU

Capacitance Measurements Using the 4200-CVU

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

To make a C-V measurement, a solar cell is connected to the 4200-CVU as shown in ***Figure 10***. Like I-V measurements made with the SMU, the C-V measurement also involves 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.

Not shown in the simplified diagram are the shields of the coax cables. The shields from the coax cables need to be connected together as close as possible to the solar cell. Connecting the shields together is necessary for obtaining the highest accuracy because it reduces the effects of the inductance in the measurement circuit. This is especially important for capacitance measurements made at the higher test frequencies.

To reduce the effects of cable capacitance, it is also important to perform a SHORT cal, OPEN cal, and Cable Correction. These simple procedures are discussed in Section 15 of the 4200-SCS Complete 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, if possible, to avoid capacitances that may be too high to measure. Also, setting the 4200-CVU to measure capacitance at a lower test frequency (10kHz) and/or lower AC drive voltage will allow making higher capacitance measurements.

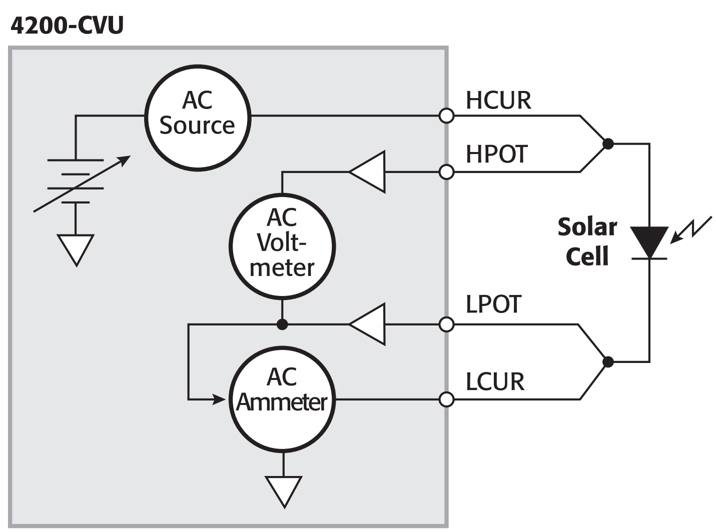

Figure 10. Connecting the 4200-CVU to a Solar Cell

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. The maximum DC current cannot be greater than 10mA; otherwise, the DC voltage output will not be at the desired level.

Figure 11 illustrates a C-V curve of a silicon solar cell generated by the 4200-CVU using the "*cvsweep*" ITM. This test was performed in the dark while the cell was reverse-biased.

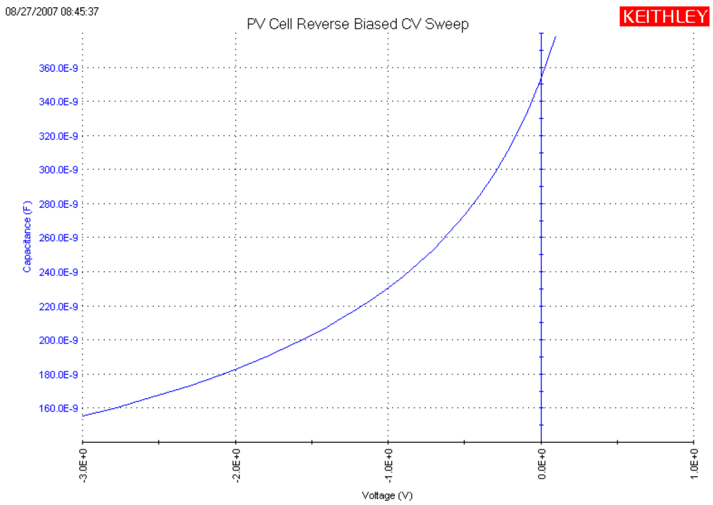

Figure 11. C-V Sweep of Silicon Solar Cell

Instead of plotting dC/dV, it is sometimes desirable to view the data as $1/C^2$ vs. V. 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 4200-CVU is shown in ***Figure 12***. This graph was generated using the "*C-2vsV*" ITM. The "Linear Line Fits" graph option can be used to derive both the doping density (N) and the built-in voltage on the x-axis. The doping density is calculated as a function of voltage in the Formulator and appears in the Sheet tab in the ITM. The user must input the Area of the device in the Constants area of the Formulator.

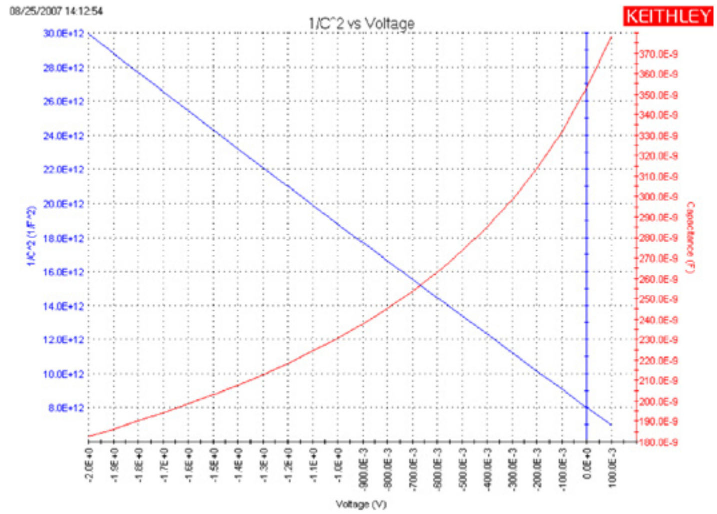

Figure 12. 1/C2 vs. Voltage of a Silicon Solar Cell

C-f Sweep

The 4200-CVU can also measure capacitance as a function of frequency. The curve in ***Figure 13*** was generated by using the "*cfsweep*" ITM. The user can adjust the range of sweep frequency as well as the bias voltage.

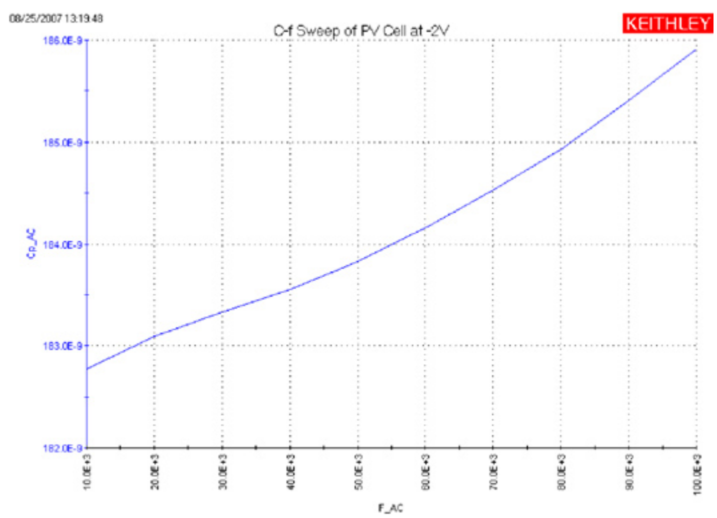

Figure 13. C-f Sweep of Solar Cell

Conclusion

Measuring the electrical characteristics of a solar cell is critical for determining the device's output performance and efficiency. The Model 4200-SCS simplifies cell testing by automating the I-V and C-V measurements and provides graphics and analysis capability. In addition to the tests described here, the 4200-SCS can also be used to make resistivity measurements on the materials used for the PV cells, a process that is described in a separate Application Note, #2475, "Four-Probe Resistivity and Hall Voltage Measurements with the Model 4200-SCS," which is available for download from www.keithley.com.

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