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Better Solar Cell Testing: The Key to Faster Development and Production

James Niemann, Keithley Instruments, Inc.

Solar cell development and production requires extensive material and device testing to improve efficiency and match individual cells for panel construction. This makes fast testing highly desirable, but requires an understanding of cell physics and their measurement implications.

Solar Energy Collection and Conversion

In many ways, solar cells operate in a manner similar to the way plants use photosynthesis to convert solar energy. Both systems are limited by quantum mechanics. Energy comes from the sun only in packets, expressed as $E = hv$, where E is energy, h is the Planck constant, and v is the frequency of the photon. A photon packet must have an appropriate quantum of energy or it is wasted.

A good deal of inefficiency is due to wavelength sensitivity. In photosynthesis, plants convert solar energy most efficiently at wavelengths in the range of 650nm to 680nm (near the peak wavelength of solar radiation at the earth's surface – see ***Figure 1***). No more useful work is done by higher energy packets (e.g., those at the shorter 400nm (violet) wavelength). The same is true for solar cells, but those made from silicon have peak sensitivity at a wavelength near 1000nm (depending on material specifics), where light intensity is lower and photon packets have about half the energy of those at 650nm (***Figure 1***).

Measurement Aims and Obstacles

Physically, a solar cell is nothing more than a specialized p-n junction (***Figure 2***) and makes use the internal photoelectric effect present in all semiconductor materials. When a photon with energy greater than the junction bandgap enters the cell, an electron is "pumped" from the valence band (below the Fermi level) to the conduction band. This causes the junction to create a forward bias potential that moves the electron into the n-type region. If an external circuit is connected to the junction (***Figure 2***), the "pumped" electron moves around the circuit and recombines with a hole in the p-type region.

A major focus of solar cell researchers and users is improving cell efficiency and maximizing energy extraction. This requires I-V measurements to characterize performance and determine the load impedance that best matches the cell's source impedance. The best match is at Point A on the I-V curve in ***Figure 3***. The cell's short circuit current intersects the y-axis (Point B) and its open circuit voltage intersects the x-axis (Point C). As much as possible, systems powered by solar cells should be designed to transfer energy to the load at Point A. No energy is delivered at Points B and C, and progressively more is delivered as the operating point approaches Point A.

Matching load impedance to source impedance becomes even more important when cells are assembled into a solar panel array. If cells are sorted by matching their I-V characteristics, those from a given bin can be assembled into a single array. Each array can then be operated at its maximum power transfer point.

Most solar cell measurement problems are related to the high capacitance associated with their forward biased p-n junctions. Compared to reverse biased junctions (e.g., photodetectors), forward bi-

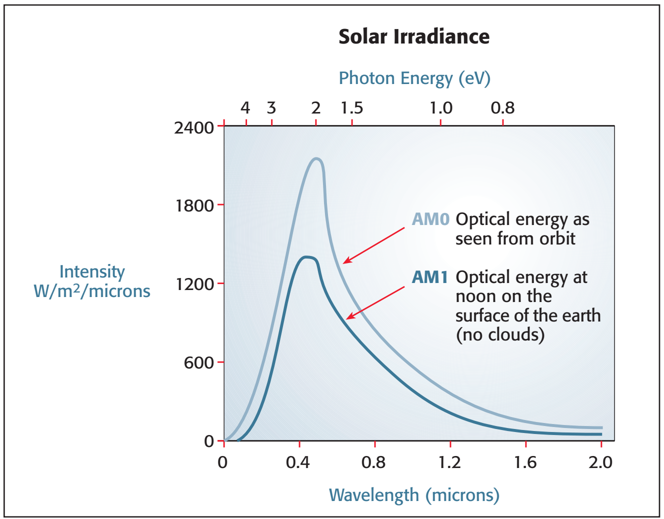

Figure 1. Approximation of solar irradiance on the earth vs. wavelength; the AM1 curve is lower than AM0 due to atmospheric attenuation.

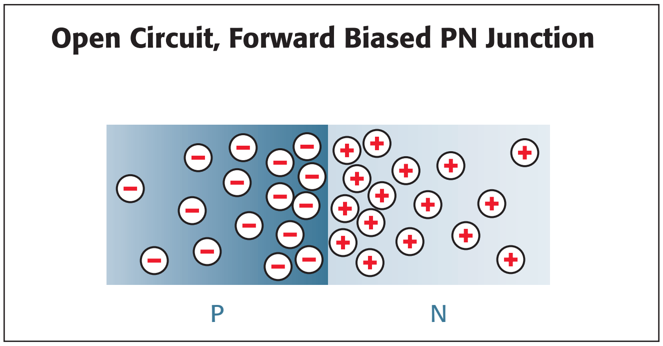

Figure 2. Representation of a solar cell p-n junction.

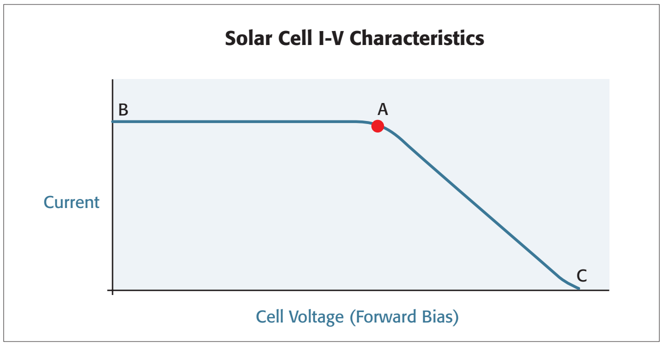

Figure 3. Forward biased solar cell I-V curve. The optimum operating point for maximum energy transfer to a load is at Point A.

ased junctions are much more capacitive because charge carriers are much closer together (***Figure 2***). As the size of the solar cell and junction area increases, the problem becomes more pronounced.

Capacitance is troublesome because it is highly desirable to make fast I-V measurements by applying a constant voltage and measuring the resulting current of the device under test (DUT). This is done by using a voltage sweep with numerous step increases to build the I-V curve (***Figure 3***). Applied forward bias voltage should be less than the cell's open circuit voltage. This simulates typical usage with a passive (resistive) load when the cell is exposed to light. In the absence of light, cell voltage is near zero with any realistic load. There is no point in testing a solar cell under reverse bias, since that condition should not occur in actual use.

The shape of the I-V curve (***Figure 3***) is governed by the cell's high Thevenin equivalent impedance. Short circuit current is determined by incident light intensity, and drops as applied voltage increases. The total circuit voltage (applied plus built-in junction potential) and incident light determine external circuit current. Current does not immediately drop as applied voltage increases, because the cell behaves as a current source over much of its I-V curve.

Measurement Methodology

To source voltage and measure current is the logical technique for fast I-V characterization of highly capacitive DUTs. A low impedance voltage source can quickly drive a solar cell to each new operating point, despite the charge required to change the voltage on a highly capacitive junction. However, a source can become unstable with capacitive loads, which may require adjustments in measurement methodology.

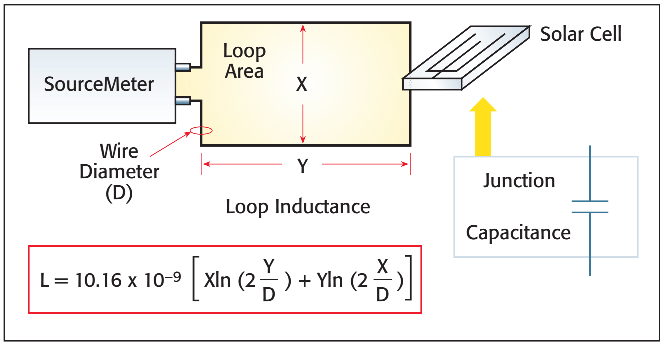

Figure 4a. Solar cell test circuits have reactive elements, i.e., lead inductance and the cell's junction capacitance. Lead inductance is a function of loop area and wire size.

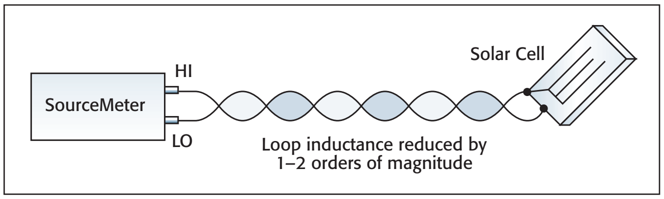

Figure 4b. Test circuit lead inductance can be significantly reduced by twisting the current carrying lead pair to reduce their loop area. This is especially important for stable voltage source operation when cell size and capacitance are large.

An alternative, sourcing current and measuring voltage, increases measurement time considerably. Low currents (lower right area of ***Figure 3***) take a great deal of time to charge cell capacitance. Furthermore, noisy measurements result at higher currents (upper left area of ***Figure 3***) due to the nearly flat I-V curve.

Another alternative is to place a variable resistance load across the solar cell. At a particular illumination, if the resistance is varied from a short circuit to an open circuit while measuring cell voltage, the I-V characteristics can be generated (i.e., $I_{load} = V_{cell}/R_{known}$).

Voltage Source Stability

When generating a solar cell I-V curve with the source voltage/measure current method, the instability of a high-speed voltage source arises because cell capacitance creates a phase shift in the system's feedback loop (***Figure 4a***). This loop includes test leads, which introduce inductance and exacerbate the problem. As shown in ***Figure 4a***, the magnitude of the inductance is determined by the dimensions of the test lead loop area.

Table 1 quantifies the effects of inductive interaction with the capacitance of various solar cells, which is a function of cell size. This table illustrates the relationship between the inductance of current carrying test leads (not the voltage sense leads, which carry no current) and the cell capacitance, resulting in the recommended voltage source bandwidth shown. Using a voltage source with higher bandwidth risks instability (oscillation) in the test circuit loop, which would yield incorrect I/V curves. Specific test situations and DUTs may place more severe limitations on voltage source bandwidth.

Note that the bandwidth is quite low (≈9Hz) in the next to last row of the table as a result of large capacitance and inductance values. Since the capacitance of the DUT is a given, the inductance must be held to a minimum. In this example, if the inductance is reduced

Test Lead Inductance, µH	Solar Cell Capacitance, µF	Max. Voltage Source Bandwidth for Test Loop Stability, Hz
0.12	0.0025	919,000
0.24	0.012	291,000
0.48	0.063	91,900
0.96	0.313	29,100
1.92	1.56	9,190
3.84	7.81	2,910
7.68	39.1	919
15.4	195	291
30.7	977	91.9
61.4	4880	29.1
123	24400	9.19
1	24400	102

Table 1. Recommended Voltage Source Bandwidth for Test Loop Stability Over a Range of Test Lead Inductance and Solar Cell Capacitance Values

from 123µH to 1µH, then the bandwidth rises to about 100Hz (last row of ***Table 1***). With such a voltage source, and allowing four time constants (4 τ) for the voltage and current to settle after a step change, reliable measurements can be made after only 6.3ms.

Adding to these problems is the fact that solar cell capacitance changes with light intensity and applied voltage. More capacitance adds more phase shift to the feedback loop, which may be marginally stable from the outset. Furthermore, noise resident in the light falling on a cell, and noise in the voltage source driving the cell, can cause additional changes in cell capacitance. Although instability may occur anywhere on the I-V curve, the probability is higher when the cell is biased near zero volts. This is due to rapid changes in cell capacitance as the junction transitions from forward to zero bias.

As cell size increases, so does the magnitude of measurement problems. Larger cells may require source currents of up to tens of amperes and instruments capable of measuring such currents. A voltage source, possibly a power supply, and two DMMs (to measure voltage and current simultaneously) could be used. Although power supplies capable of driving a capacitive load are available, most are not designed for rapid voltage sweeps with such loads. Many of these supplies have internal compensation circuitry that results in long settling times for a step change in voltage. Generating a solar cell I-V curve with this type of source could take too long, particularly in an automated test environment.

Test throughput can suffer further when a PC controls the instruments over the GPIB (General Purpose Instrument Bus). Even if a high speed power supply were used, it would have to be programmed over the GPIB for every measurement point on the I-V curve. DMM voltage and current measurements transmitted to the PC over the GPIB add to the length of a test cycle.

Measurement Solutions

A number of reasonably priced instruments are available to source and measure DC signals for solar cell I-V characterization. The choice usually hinges on speed and accuracy issues. As long as steps are taken to avoid instabilities in a high-speed source, the source voltage/measure current method usually produces the best results.

Regardless of instruments used, lead inductance can be mitigated with a cabling system that reduces the test lead loop area. This area can be large, because the DUT may not be near the voltage source. Fortunately, inductance can be reduced very easily by twisting a pair of leads. (See ***Figure 4b***.) Twisted pairs also reduce noise that would be magnetically coupled into the leads.

Twisting is most important for the output HI and LO leads, which carry source current, as opposed to the voltage source remote sense leads. Remote sensing of source voltage at the solar cell with a separate pair of leads avoids inaccuracies due to voltage drop when power leads are used for voltage sensing. (Separate sense leads carry negligible current because they are connected to the source's high impedance input amplifier.)

Changes in capacitance with applied cell voltage may be more troublesome, since changing capacitance represents a squared reactive element that creates additional phase shift in the test circuit (feedback) loop. The easiest way to eliminate this effect is to close the loop in a way that prevents this squared reactance from becoming a problem. This can be done by adding pure capacitance across output HI and LO terminals of the voltage source. If enough capacitance is added (approximately the same capacitance as the biased solar cell) then the loop will be closed before the additional phase shift of the reactive elements can cause the test loop to become unstable. Nevertheless, an appropriate voltage source should be selected from the outset. It is best to start with a fast step response source, and then add just enough external capacitance for stability.

Measurements on Large Cells

With an exceptionally large cell area, the problems just discussed may be insurmountable and require a different solution. The source current, measure voltage method may be unavoidable, although it represents a compromise with respect to noise error and speed in I-V measurements.

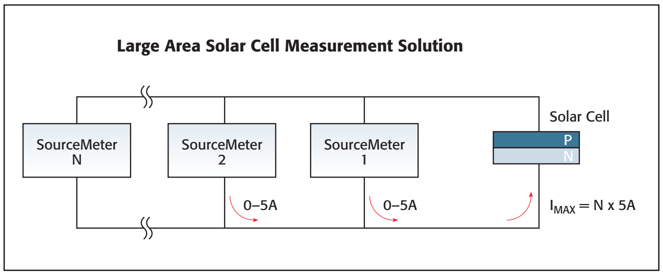

Figure 5. Multiple source-measure instruments can be used to get sufficient drive current for I-V characterization of large solar cells and panels.

Even so, appropriate instrumentation can reduce test time. A source-measure instrument (also called a SourceMeter® instrument) can simultaneously apply the source current and measure solar cell voltage. These instruments integrate the functionality of a source (voltage or current) and all the measurement functions of a DMM. (Their advantages also apply to the source voltage/measure current mode used with smaller cells.) Their source current mode allows more than one source to be placed on the load, each individually adding current to the cell. ***Figure 5*** shows an illuminated solar cell loaded with several parallel-connected current sources.

With parallel sources, I-V measurements begin with all sources configured for zero current, allowing the open circuit voltage of the solar array to develop under applied illumination. The test sequence can be programmed for a current ramp that spans as many sources as needed to reach the required maximum. When the first source reaches full scale current, the next source in the system continues to add additional current into the array, and so on. All current sources should be advanced in accordance with the current polarity of a normally operating solar cell, as shown in ***Figure 5***.

A SourceMeter hastens I-V characterization by combining a high speed source with the inherent advantages of integrated source and measurement functions. A novel characteristic of these instruments is a source function that supports four-quadrant operation (***Figure 6***). This allows it to function as a variable sink (or load) for a solar cell. With four-quadrant operation, if the output voltage is positive, current can flow both into and out of the HI terminal while the programmed voltage remains stable. Conversely, a positive current can be programmed into either a positive or a negative voltage source. The unit can also switch automatically between source voltage and source current modes when the load demands more voltage or current than a preset maximum.

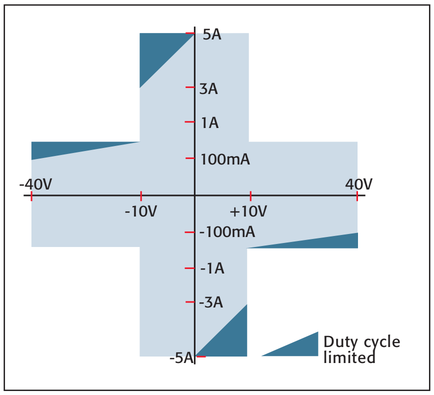

Figure 6. Four-quadrant operation of a SourceMeter allows it to act as either a source or a load during solar cell tests; when acting as a source, it can rapidly switch between voltage and current modes.

Although a DC source and two DMMs could be used for solar cell I-V characterization, a SourceMeter avoids test system integration problems. Moreover, this type of instrument allows rapid voltage and current sweeps, quickly switches modes, and simultaneously takes all readings with a high accuracy measuring circuit (typically, 5½-digit resolution).

Moreover, most of these instruments have firmware that avoids throughput reductions resulting from separate DMM and voltage source control over the GPIB. Typically, the firmware requires only start and stop signals for control via the GPIB. Also, large internal buffers allow data accumulation until there is an idle period on the GPIB before readings are sent to the PC controller. This combination of features provides a huge throughput advantage compared to separate GPIB instruments. KEITHLEY

About the Author

James Niemann is a Staff Engineer with Keithley Instruments in Cleveland, Ohio, where he is responsible for designing instrumentation used in low level measurements. He earned a Bachelor of Science degree in Electrical Engineering from the University of Akron. He has been awarded three patents for his work and has 14 years of experience in instrumentation design.

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Keithley Instruments, Inc. 28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168
1-888-KEITHLEY (534-8453) • www.keithley.com

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