SOLAR SIMULATORS AND I–V MEASUREMENT METHODS

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1. Introduction

The illuminated current *versus* voltage (*I–V*) characteristics of a photovoltaic (PV) device typically measured with respect to standard reference conditions, are defined by a spectrum, intensity, temperature and area. Factors that influence *I–V* measurements include voltage sweep rate and direction, contact to the metallization, light source, junction temperature, instrumentation and intensity. The merits and problems of various procedures influencing the repeatability and accuracy of *I–V* data are discussed.

The photovoltaic conversion efficiency is defined as 100 times the maximum power produced by the PV device divided by the incident light power under standard reference conditions. A variety of solar simulators used by the PV community, which approximate a standard reference solar spectrum and intensity are compared using the ASTM procedure for determination of the simulator class. The spectral mismatch index can also be used to evaluate differences in the relative spectral irradiance of a solar simulator for the particular test-cell/reference-cell combination of interest. Several methods of enhancing the ability of solar simulators to match a given reference solar spectrum and intensity are described. They include real time intensity corrections, spectral mismatch corrections and compensation for spatial non-uniformity of the light source.

2. Area definitions

The efficiency is proportional to the area definition of the device (cell or module) being tested. The controversial subject of the area definition for a particular device is discussed. The published standard area definitions are as follows.

(1) The entire front surface area of the cell, including area covered by grids and contacts (for concentrator cells, test cell area is the area designed to be illuminated) [1].

(2) Frontal area of the cell under test including the area covered by the grids and contacts [2].

(3) The entire frontal area of the solar cell, including the contact grid [3].

These area definitions are all essentially the same and are sometimes referred to as total area definitions. A wide variety of definitions for the cell area is being used by the PV community, including the following list.

(1) Area defined by the electrically active junction.

(2) Total surface area minus the maximum area that can be physically removed without affecting the cell performance.

(3) Area of the junction as determined by processing (diffused area, conducting oxide, photolithography, etc.).

(4) Area defined by a mesa etch.

(5) Device area illuminated by light.

(6) Maximum area that when exposed to light generates a certain percentage of the I_{sc} generated when the whole cell is exposed to light and possibly the contact pad or grid area.

(7) Total area minus the grid and contact pad area.

(8) Total cell area minus the area designed to accommodate the contact pad.

(9) Area determined by weighing the substrate and using the published substrate density.

(10) Weight of a photograph of the cell compared with the weight of a photograph of a known area.

(11) Area measured by a laser scanner where the border is defined as the location where the photocurrent drops to a given percentage of the maximum.

(12) Area determined by the shadowmask area used to deposit the film through.

(13) The area of the conducting oxide or contact area to the back surface for superstrate cells.

(14) The area supplied by the manufacturer.

The published standard area definitions for a module or submodule are as follows.

(1) The entire frontal area including borders and frame [1].

(2) The entire frontal area of the module, including borders, frame and any protruding mounting lugs [3].

These module or submodule area published definitions are essentially identical; however, many other module area definitions are being used by the PV community including the following.

(1) Total projected (frontal) area minus the area of the wire on the side.

(2) Area of the PV material that is actually exposed to light.

(3) Total PV area minus the area lost to scribing, gaps, bus bars, frame etc.

(4) Area supplied by the manufacturer.

The area definitions used by the PV community can account for large differences (over 100%) in the efficiency between various groups. The extreme case of 350% difference between the reported area of a submodule and the definition in ref. 1 occurred because the device was on a glass superstrate with a large area lost to gaps, scribe marks, and interconnects. The lack of an accepted area definition that is independent of a particular device structure is a problem that must be resolved before a fair and meaningful comparison of efficiency measurements between various groups and technologies can be made. The published standard area definitions are essentially identical and independent of the technology.

3. Classification of solar simulators

The ASTM procedure of the classification of a solar simulator is summarized in Tables 1 - 3 [4]. The spatial non-uniformity of a simulator improves as the focal length of the simulator increases. The spatial non-uniformity in and above the test plane is a strong function of the user's ability to properly align the bulb for all arc simulators. The temporal instability of a simulator which mainly affects the current can be improved

TABLE 1

Classification of a solar simulator using the ASTM procedure [4]

	Class		
	A	*B*	*C*
Spatial nonuniformity	$< \pm 2\%$	$< \pm 5\%$	$< \pm 10\%$
Temporal instability	$< \pm 2\%$	$< \pm 5\%$	$< \pm 10\%$
Total irradiance within a 30° field of view	$>95\%$	$>85\%$	$>70\%$

TABLE 2

Spectral classification of simulator

Class	$\dfrac{\textit{Simulator spectrum in wavelength band (\%)}}{\textit{Reference spectrum in wavelength band (\%)}}$
A	0.75 - 1.25
B	0.6 - 1.4
C	0.2 - 2.0

TABLE 3

Percent of total irradiance between 0.4 and 1.1 μm of reference spectrum within the given wavelength intervals

Wavelength interval (μm)	*Percent of reference spectrum normalized for the 0.4 - 1.1 μm wavelength range*			
	Direct spectrum		*Global spectrum*	
	[5]	[8]	[7]	[8]
0.4 - 0.5	18.0	15.6	18.9	18.5
0.5 - 0.6	18.6	19.9	21.0	20.1
0.6 - 0.7	18.0	17.4	17.5	18.4
0.7 - 0.8	15.5	15.9	14.8	14.8
0.8 - 0.9	13.3	11.5	11.5	12.3
0.9 - 1.1	18.6	17.9	16.3	16.0

TABLE 4

Classification of several solar simulators using the procedure in Tables 2 and 3

Light Source	*Standard spectra*	*Class*	*Light source/reference spectra wavelength interval* (μm)					
			0.4 - 0.5	0.5 - 0.8	0.6 - 0.7	0.7 - 0.8	0.8 - 0.9	0.9 - 1.1
Outside direct	[6]	B	1.23	1.06	1.07	0.92	0.88	0.83
	[8]	A	1.03	1.05	1.01	0.99	0.96	0.93
Outside global	[6]	A	1.13	1.02	1.06	0.97	0.97	0.86
	[8]	A	0.95	1.01	1.00	1.04	1.05	0.96

ELH (120 V, diffuser)	[6]	C	0.59	1.09	1.65	1.45	0.58	0.54
	[8]	C	0.29	1.08	1.56	1.56	0.63	0.60
ELH (60 V)	[6]	—	0.26	0.74	1.55	1.71	0.79	0.93
	[8]	—	0.22	0.73	1.46	1.84	0.85	1.04
ELH (120 V)	[6]	C	0.65	1.13	1.67	1.42	0.52	0.29
	[8]	C	0.55	1.12	1.58	1.53	0.56	0.54
Spectrolab XT10 A	[6]	C	0.70	0.63	0.74	0.79	1.60	1.67
	[8]	C	0.59	0.62	0.70	0.84	1.72	1.87
Spectrolab XT10 B	[6]	B	0.99	0.87	1.05	1.12	1.38	0.72
	[8]	C	0.83	0.86	0.99	1.20	1.49	0.80
Spectrolab X25	[6]	B	1.31	1.10	1.10	0.81	0.77	0.81
	[8]	A	1.11	1.09	1.04	0.87	0.83	0.96
Optical Radiation Co.	[6]	B	1.03	0.85	0.91	0.79	1.03	1.39
	[8]	C	0.87	0.85	0.86	0.85	1.11	1.55
Oriel A	[6]	B	1.24	1.28	1.23	0.88	0.86	0.63
	[8]	B	1.05	1.12	1.16	0.95	0.93	0.71
Oriel B	[6]	B	1.35	1.00	1.04	0.93	0.65	0.95
	[8]	B	1.14	0.99	0.99	1.00	0.70	1.10
	[7]	A	1.11	0.95	1.04	1.00	0.75	1.08
CSI-Thorn	[6]	C	0.69	1.56	1.53	0.69	1.02	0.64
	[8]	C	0.58	1.55	1.44	0.74	1.11	0.71
WACOM Wantabe	[6]	B	0.98	1.07	1.22	0.92	0.61	1.08
	[8]	B	0.83	1.06	1.16	0.99	0.66	1.21
Spectrolab LAPSS, Global	[6]	B	1.39	0.96	0.91	0.82	0.96	0.96
	[8]	A	1.18	0.96	0.86	0.89	1.04	1.08
Spire SPI-SUN model 240	[6]	A	1.18	0.99	1.15	0.82	1.14	0.87
	[8]	A	0.99	0.99	0.99	0.89	1.07	0.97

by an order of magnitude or more by correcting real time for intensity fluctuations with an intensity monitor and a computer-controlled data acquisition system. The correction for intensity variations over the *I–V* measurement period is essential for accurate measurements with a pulsed simulator. Most simulators have 95% of the total irradiance within a 30° field of view. Table 4 lists the spectral classification for several solar simulators using the procedures given in Tables 1 and 2. The spectral irradiances for the light sources were measured at SERI with a LICOR spectroradiometer [9] whenever possible. The spectral irradiance of the CSI, WACOM and Spire solar simulators were supplied by the manufacturers. The Spectrolab LAPSS spectral irradiance was supplied by the Jet Propulsion Laboratory (Pasadena, CA, U.S.A.). The spectral irradiance data used in this study are not necessarily representative of the solar simulator used at a given laboratory and are intended only for illustrative purposes. The spectral irradiance for most solar simulators changes with the bulb age, current and cleanliness of the optics. The measured direct normal spectral irradiance under natural sunlight and clear sky conditions at SERI can be treated as a Class B solar simulator for the direct standard spectrum in ref. 6 (too much energy in the 0.3 - 0.4 μm wavelength interval). This same measured direct normal spectral irradiance can be treated as a class A solar simulator for the global standard spectrum in ref. 8. A "typical" clear sky global normal spectral irradiance measured at SERI can be treated as a class A global and direct normal solar simulator. The ELH or more generally tungsten–halogen bulb with dichroic filter simulator is a class C solar simulator because of a lack of energy in the 0.4 - 0.5 μm wavelength interval and too much energy in the 0.7 - 0.8 μm range. The spectral irradiance for the Spectrolab XT10, Oriel, and Optical Radiation Company Xe arc solar simulators are class B to C; however, the manufacturer can probably improve the spectral match to the standard spectrum by using a different filter package. The Spectrolab X25 is a class A global simulator, but like all continuous Xe arc solar simulators the energy in the 0.4 - 0.5 μm wavelength interval decreases while the energy in the 0.9 - 1.1 μm wavelength interval increases with bulb age. The Spectrolab and Spire pulsed simulators have the closest spectral match to the standard solar spectrum.

The spectral classification of a solar simulator can also be evaluated by examining the spectral mismatch [10] for the particular test device, reference cell and standard spectrum of interest. The spectral mismatch index for a single-crystal and filtered single-crystal silicon reference cell used to measure and set the intensity of a solar simulator for an amorphous silicon test device (Fig. 1) is shown in Table 5 for the same light sources evaluated in Table 4. The use of a filtered silicon reference cell reduces the error due to spectral mismatch to less than 1% in all cases except for the CSI lamp (4%). Even though tungsten–halogen light sources are poor simulators due to the spectrum shift with age and spatial nonuniformity, the error from spectral mismatch was reduced to 1% when using a filtered silicon reference cell to evaluate an amorphous silicon PV device for the

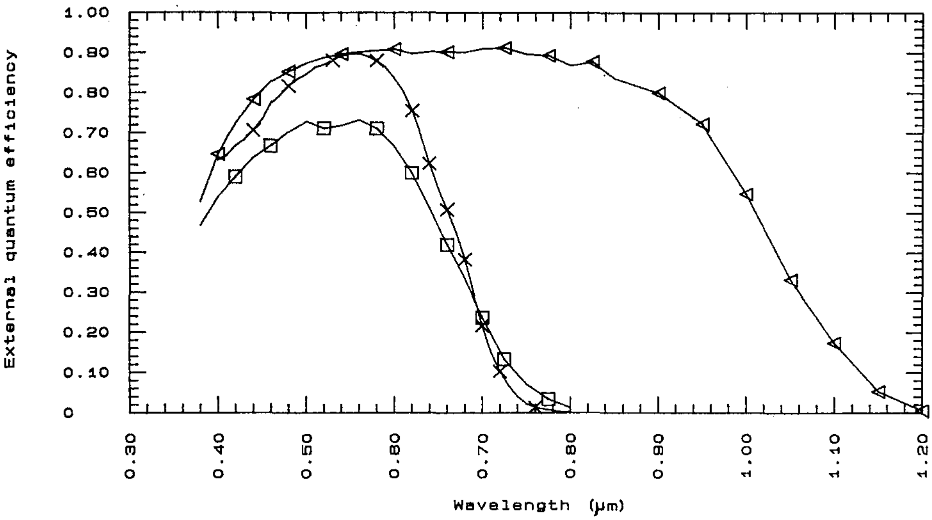

Fig. 1. External quantum efficiencies for a single crystal silicon reference cell (triangle), filtered silicon reference cell (rectangle) and a typical amorphous silicon test device (cross).

TABLE 5

Spectral mismatch factor for several light sources using global reference spectrum in ref. 4 for an amorphous silicon test cell (Fig. 1)

Light source	*Mismatch index*	
	Crystal Si reference cell (Fig. 1)	*Filterered Si reference cell (Fig. 1)*
Outside direct	1.0309	1.0047
Outside Global	0.9847	1.0033
ELH (120 V, diffuser)	1.0264	1.0109
ELH (60 V, no diffuser)	0.7647	0.9931
ELH (120 V, no diffuser)	1.0764	1.0121
Spectrolab XT-10 A	0.5940	0.9905
Spectrolab XT-10 B	0.8535	0.9893
Spectrolab X-25	1.0841	1.0051
Oriel A	1.1217	1.0065
Oriel B	1.0541	0.9883
Optical Radiation Co.	0.8393	0.9930
Wacom/Wantabe Co.	1.0248	0.9997
CSI-Thorn Lighting	1.2063	1.0397
Spectrolab LAPSS	0.9737	0.9920
Spire SPI-SUN 240	0.9855	0.9979

particular light sources evaluated here. The variation in tungsten-halogen light sources from bulb to bulb can be substantial causing large variations in the spectral mismatch.

4. *I–V* Measurements

Once the solar simulator intensity has been set to match the standard intensity and spectrum using a reference cell for the particular device being evaluated the *I–V* characteristics can be measured. The minimum specifications for *I–V* measurement instrumentation are discussed in refs. 1 - 3. If the voltage sweep rate for the PV device being evaluated is too large, then the fill factor and efficiency can be artificially high. The cell should be mounted on a temperature-controlled plate with the junction temperature at the standard test temperature (25 or 28 °C). The plate temperature can be controlled by gas, water, or most reliably with a thermoelectric module. The device temperature can be measured with a thermistor, thermocouple, platinum RTD, optical pyrometer or surface temperature probe. Superstrate PV devices represent a problem in temperature control and measurement which can be alleviated by blowing air over the sample or using a pulsed solar simulator to minimize light exposure time (device temperature same as room temperature).

Contact to the PV device with a vacuum plate can be achieved by: mounting a plated Ni or Au printed circuit board (voltage contact) in a slot in the vacuum plate (current contact); mounting a spring loaded probe (voltage) in the vacuum plate (current); or by using Kapton plated with patterned Cu or Ni for electrically isolated voltage and current contacts to the device substrate. A variety of probe designs available for making contact to PV devices are summarized in Table 6. The fill factor and efficiency can be artificially enhanced by separating the voltage and current contacts or by adding multiple current contacts making poor grid designs appear optimal. Too small a current contact area can cause current crowding (localized heating) reducing the fill factor and efficiency. Whenever possible the resistance between the voltage and current contacts should be measured when making contact to the device so that contact to the device can be achieved with a minimum amount of force. The resistance between the voltage and current contacts should be less than 5 Ω. Custom test fixtures are useful for the rapid evaluation of PV devices in a production environment. Silver paste or silver epoxy is sometimes used because it provides a convenient means of attaching wires for subsequent testing. Attaching wires with solder or an ultrasonic bonder is essential for evaluating concentrator cells because of the large currents. The use of metallized rubber is popular in evaluating superstrate cells because large area contacts can be made to thin metallizations without damage. A kelvin probe is useful because electrically isolated voltage and current contacts can be made with the same manipulator.

TABLE 6

Probe contacts to a PV device

Contact type	*Material*	*Comments*
Dagger	Os, W, Au, Ag	Readily available, tip can be bent, small contact area
Spring loaded	Au plated	Contact force repeatable
Homemade	Brass, Cu, In, wire	Low cost, can be designed for specific applications
Bonded wire	Ultrasonic	Reduces resistance
	Soldered	Required for concentrators
	GaIn eutectic	Leaves residue
	Ag paste	Convenient
Custom test fixture	W, Au, Ag	Simulate soldered contacts, automated testing
MSI Corp. "C" probe	Au plated Cu	Large contact area, easy to bend wire.
Metallized rubber		Contact area defined by size of rubber, will not scratch
Kelvin probe	W, Os, Au	Voltage and current contact can be made with same manipulator, fixed and narrow spacing between voltage and current contact

5. Summary

Large differences in reported efficiency can occur because of differences in area definition and measurement, spectral mismatch errors and reference cell calibration. The performance of a solar simulator is site specific. A simulator bulb type, age, current and alignment can affect the spatial uniformity, temporal stability and spectral irradiance of the simulator. Alignment and cleanliness of the simulator optics will affect the spatial uniformity and spectral irradiance. The measurement procedures including corrections for intensity fluctuations and measurement of the simulator intensity with a reference cell will affect the accuracy and repeatability of *I–V* measurements. The spectral irradiance of the solar simulator should be measured periodically on site for spectral mismatch calculations. Not all outdoor clear sky spectra satisfy class A solar simulator requirements or match a reference spectrum as well as pulsed Xe arc solar simulators.

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