

MODELLING THE MEASUREMENT OF SILICON SOLAR CELLS UNDER NATURAL SUNLIGHT

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ABSTRACT: This paper presents results from a modelling study aimed at determining the likely error in cell efficiency that will result if solar cells are measured under natural sunlight relative to a calibrated reference cell or a pyranometer. Since AM1.5G conditions are often not accessible it is interesting to determine whether other air mass conditions are suitable for outdoors measurements. The conclusion is that a wide range of air mass, water vapour and turbidity conditions can be used for cell measurement without causing significant errors provided that a few precautions are taken. Outdoors measurements are much cheaper and simpler than accurate simulator measurements and many of the potential error sources are eliminated.

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1. INTRODUCTION

Accurate measurement of silicon solar cells comes in two forms: the need to reliably measure relative efficiencies to allow sorting of cells; and the need to have an absolute measurement of a (usually) smaller number of cells. Reliable relative cell measurement does not require a sophisticated and expensive measurement system. Reliable absolute cell measurement usually reduces to the accurate measurement of the short circuit current.

Measurement of fill factor to within a fraction of a percent is straightforward provided that a 4 point probe technique is used to eliminate contact resistance. Measurement of voltage to within a few mV merely requires that the temperature of the cell be close to 25°, which can be accomplished with the aid of a test block with an embedded thermocouple and with some form of cooling. In fact, control of the cell test block does not have to be very good since cell temperatures between 15° and 35° can easily be corrected for by subtracting or adding 2 to 2.5 mV per degree (depending on cell V_{OC}) to the observed open circuit voltage.

Measurement of short circuit current is where most cell measurement error arises. Accurate measurement of J_{SC} is normally done relative to a calibrated reference cell combined with the use of a spectral mismatch correction factor (M). Accurate measurement of M for a particular cell is much more time consuming and expensive than the other aspects of cell measurement [1,2]:

- the relative spectral irradiance of the simulator must be measured regularly;
- the instrument used to measure the spectral irradiance of the simulator must be regularly calibrated;
- the flux uniformity of the simulator must be periodically measured;
- the relative spectral responsivity of the reference cell must be periodically measured;
- the relative spectral responsivity of the test cell must be measured;
- the monochromator and detectors used to measure spectral responsivity must be regularly calibrated.

Not one of these steps would be required if outdoors measurements were to yield sufficiently small spectral mismatch correction factors. The purpose of this paper is to show that outdoors testing of solar cells can be more accurate and reliable than all but the most careful simulator measurements.

2. CELL MODELLING WITH PC1D

The one dimensional solar cell modeling program PC1D [3] was used to calculate silicon solar cell short circuit currents for a range of key cell parameters. The parameters listed below determine in a rather general way the important generation and recombination processes within solar cells. Other parameters are of secondary

importance. The values chosen for each of the parameters bracket the likely values to be found in a silicon solar cell.

- **3 minority carrier diffusion length in the cell (L_n):** 40, 100 or 1,000 microns
- **3 recombination velocities in the front surface region (S_f):** 10, 10^4 or 10^5 cm/sec
- **2 recombination velocities in the rear surface region (S_r):** 10 or 10^4 cm/sec
- **2 thicknesses of the base region of the cell (W_b):** 100 or 300 microns
- **2 internal reflectivities of the rear surface:** 50% or 90%
- **2 light trapping qualities:** textured Lambertian (excellent) and polished (poor)

Seven different solar spectrums were used: AM0, AM1.5D, AM1.5G, AM1D (clear air), AM1D (turbid air), AM4D (clear air) and AM4D (turbid air). The first three spectrums were from PC1D while the next four were from [4]. The data in [4] is in the form of an algorithm which can be readily analysed with a spreadsheet. Here D and G refer to direct and global spectrums.

PC1D was run 1008 times, spanning the parameter space of the three diffusion lengths, the three front surface recombination velocities, the two rear surface recombination velocities, the two cell thicknesses, the two rear surface reflectivities, the two qualities of light trapping and the seven different solar spectrums. The other parameters chosen for the study were as follows:

- Cell base resistivity of 1 ohm-cm (n^+/p).
- Front surface diffusion: erfc profile, 0.4 microns deep, maximum doping of 10^{19} cm⁻³
- No rear surface diffusion
- Front surface AR coating of silicon nitride ($n=1.9$)
- Material properties as for single crystal silicon
- Excitation: 100 mW/cm², 25 deg

Although only one resistivity was examined, the range of diffusion lengths chosen was sufficiently large to span the likely range of diffusion length - doping density products.

The material properties were chosen to be those of single crystal silicon. Provided that the defect density is not very high within grains this is a reasonable assumption also for multicrystalline silicon. Grain boundaries, of course, can cause some of the bulk material properties such as mobility to differ substantially from those of single crystal silicon. In small grained silicon the effective diffusion length will be determined by the grain size and not by the intrinsic material quality.

3. SOLAR SPECTRUMS

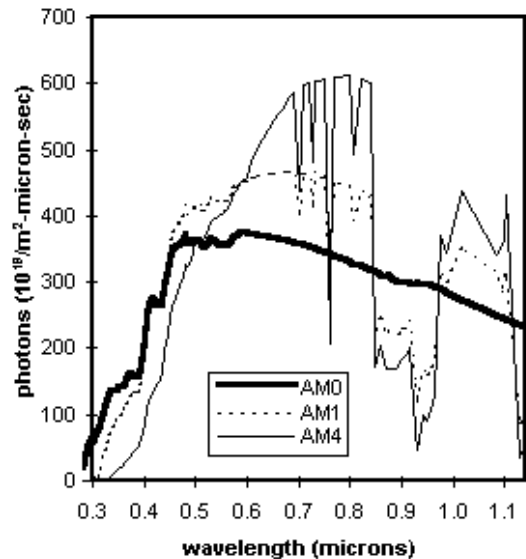
For sunlight intensity normalised to 100 mW/cm² and a water vapour column of 20 mm the following observations can be made:

- The solar spectrum changes as the air mass increases, with an overall shift from the UV to the IR.
- Additional water vapour cause a shift from the IR to the near IR and visible.
- Turbid air results in a small shift towards the IR.

The spectral changes listed above are not large. When the solar intensity is above 40 mW/cm² the wavelength region 500 nm to 840 nm has 62% +/- 5 % of the useable photons (<1120 nm) independent of air mass, water vapour content and turbidity. The blue and UV region (<500 nm) has 10% to 15% of the photons depending mainly on air mass while 20% to 30% of the photons are in the wavelength range 840-1120 nm.

Increased air mass and turbidity causes increased solar absorption by the atmosphere across the whole spectrum (slightly less in the IR), while water vapour strongly absorbs above 840 nm (see Fig. 1).

Figure 1: Photon spectral distribution for AM0, AM1 and AM4 normalised to 100 mW/cm². The AM1 and AM4 spectra are for clear skies.



Most silicon solar cells have high (>85%) internal quantum efficiency (IQE) in the wavelength region 500 nm to 840 nm (the onset of strong water vapour absorption). Different values of diffusion length and surface recombination rates affect IQE mainly in the UV and IR, which contain fewer than 40% of the photons. In general the quality of the blue response of a solar cell will be similar to that of the red response.

From the above discussion it can be seen that provided that outdoors cell measurements are made under reasonably sunny conditions (intensity > 40 mW/cm²) shifts in the spectral distribution of sunlight caused by changes in air

mass, turbidity and water vapour content are not likely to cause large changes in the ratio of the short circuit currents of the test and calibrated reference cells. This is borne out in the analysis below.

4. MODELLING OUTDOORS CELL MEASUREMENT

Cell measurements are normally made relative to a calibrated reference cell. Light intensity is adjusted to yield the calibrated short circuit current of the reference cell. Solar intensity cannot be adjusted except by choosing a different time of day. However, if cell current responds linearly to light intensity (as nearly all solar cells do in the vicinity of 100 mW/cm² illumination) then a simple arithmetic adjustment can be made to the current of the cell being tested to yield the correct short circuit current.

This process was modelled for the short circuit currents of the 1008 cell-spectrum combinations described above. Their currents were compared with those of 5 reference cells and a pyranometer (Table I). The reference cells were chosen to be representative of likely reference cell types.

Table I: Reference cell descriptions. Cell thickness is 300 microns and rear surface reflectivity is 90% in each case.

Reference	L _n microns	S _f cm/sec	S _r cm/sec	surface
1	1,000	10 ⁴	10 ⁴	polished
2	100	10 ⁴	10 ⁴	textured
3	1,000	10 ⁵	10 ⁴	textured
4	1,000	10 ³	10 ³	textured
5	1,000	10 ⁴	10 ⁴	textured
pyranometer	uniform response for all wavelengths			

By definition under AM1.5G, 100 mW/cm² illumination there is no spectral mismatch. Both the test and reference cells will display their true short circuit currents. Under a different spectrum there will be a mismatch, since the currents of the test and reference cells will respond in slightly different ways to the changed spectral distribution. The extent of this spectral mismatch was determined for each of the 1008 cell-spectrum combinations with each of the five reference cells and the pyranometer (total of 6048 combinations). The average mismatch error was determined for each reference cell together with the highest and lowest values of mismatch error. These appear in Table II.

The mismatch error is small for silicon reference cells, generally less than 2%. The worst error that would occur from all the combinations of silicon test and reference cells is 4.3%. The standard deviation from the average for each spectrum-cell combination was between 0.8% and 1.3%.

If reference and test cell are chosen to have a similar design then the largest error would be +/- 2%, with most reference/test cell combinations having errors of +/- 1%. Even the use of an AM4 spectrum does not cause large mismatch errors, although they are slightly larger than for

AM1. These uncertainties compare favourably with those from a sophisticated simulator system [2].

The mismatch error is larger for a pyranometer since it responds in a different way to silicon cells to changed spectral distributions. This is particularly so for AM0 which has considerably more photons in the UV and infra red regions than in the visible region of the spectrum.

Table II: Mismatch errors for various air masses relative to AM1.5G.

		Zero	1D clear	1D turbid	1.5D clear	4D clear	4D turbid
Ref1	Min	-1.1%	-1.0%	-1.1%	-2.6%	-2.6%	-2.7%
	Max	2.1%	2.0%	2.1%	2.3%	2.6%	2.6%
	Ave	0.4%	0.6%	0.7%	-0.7%	0.0%	-0.3%
Ref2	Min	-2.4%	-1.6%	-1.7%	-1.5%	-1.2%	-1.1%
	Max	0.7%	1.4%	1.5%	3.5%	4.0%	4.3%
	Ave	-0.9%	0.0%	0.1%	0.5%	1.4%	1.4%
Ref3	Min	-1.1%	-0.7%	-0.8%	-3.5%	-2.9%	-3.8%
	Max	2.1%	2.4%	2.4%	1.4%	2.3%	1.5%
	Ave	0.4%	1.0%	1.0%	-1.6%	-0.3%	-1.4%
Ref4	Min	-2.7%	-1.1%	-1.3%	-2.6%	-1.0%	-1.8%
	Max	0.4%	1.9%	1.9%	2.3%	4.3%	3.5%
	Ave	-1.2%	0.5%	0.5%	-0.7%	1.7%	0.7%
Ref5	Min	-2.4%	-1.1%	-1.2%	-2.4%	-1.1%	-1.6%
	Max	0.7%	1.9%	2.1%	2.6%	4.1%	3.7%
	Ave	-0.9%	0.6%	0.6%	-0.5%	1.5%	0.8%
pyran	Min	-10.8%	-3.1%	-4.7%	-4.5%	-2.0%	-8.0%
	Max	-8.0%	-0.1%	-1.6%	0.3%	3.2%	-3.1%
	Ave	-9.5%	-1.4%	-3.0%	-2.7%	0.7%	-3.8%

5. PERFORMING OUTDOOR CELL MEASUREMENT

A simple and accurate method of performing an outdoors measurement is to measure the FF and V_{OC} indoors under a simulator with approximately the correct light intensity and to measure the J_{SC} outdoors relative to a calibrated reference cell or pyranometer. The V_{OC} and FF will not be significantly affected by large changes in spectral content or modest changes in illumination intensity. A test jig can be easily constructed that can be mounted normal to the sun, that has an in-built reference cell and that has a simple battery powered voltage offset to reach the J_{SC} point. Each cell measurement using such a jig only requires a minute or two.

The J_{SC} of six silicon cells were measured outdoors under air masses ranging from 1 to 2.7. Air mass was

corrected for solar refraction and the altitude of the test site. The cells ranged in quality from high performance devices to multicrystalline cells with effective diffusion lengths of about 30 μm . Clear skies prevailed during the measurements. The variation in short circuit current of the 6 test cells relative to the reference cell (a good quality silicon cell) was less than $\pm 2\%$, which supports the conclusions of the PC1D modelling.

6. DISCUSSION

Outdoors measurement of cells under natural sunlight has a number of significant advantages over simulator measurements. These include:

- any size of cell can be measured with absolute spatial illumination uniformity;
- properly collimated light is available;
- uncertainties associated with the spectral content of the simulator are replaced by the much smaller uncertainties associated with deviation of sunlight from AM1.5G;
- uncertainties associated with aging of lamps, filters, detectors etc are eliminated;
- the method is very inexpensive, quick and simple compared with a simulator of comparable accuracy;
- there is a very small spectral mismatch correction factor for almost any test cell, reference cell and spectrum combination;
- there is easy access to accurate and reliable cell efficiency measurements without the need to send cells to distant measurement facilities

Precautions that need to be taken include:

- check cell linearity with light intensity in case the solar power is not above about 80 mW/cm^2 ;
- ensure that cell temperature does not depart too far from 25° (J_{SC} is not very sensitive to temperature);
- test on clear days when the light intensity is above 40 mW/cm^2 ;
- ensure that the cell is perpendicular to the sun;
- ensure that there is a low level of indirect light (eg clouds near the sun, haze or strong reflections from nearby surfaces);
- check that the ratio of J_{SC} from a variety of test cells relative to a reference cell does not change significantly during the course of a day - this will give confidence in the method;
- periodically check that the reference cell current has not altered over time with the aid of a stable primary reference or pyranometer.

Clearly the major error source is the tendency for reference cells to drift downwards in output over time. If this is not detected then cell currents will be overestimated. This source of error applies equally to both outdoors and simulator measurements. Visual observation and monitoring the open circuit voltage of a reference cell

(which is sensitive to similar degradation modes to current) will normally pick up this problem.

7. CONCLUSION

The conclusion of this work is that an outdoors test relative to a reference cell or a pyranometer is an accurate method of determining cell current. Spectral mismatch error will be small. Indeed, outdoors testing of solar cells is likely to be more accurate and reliable than all but the most careful simulator measurements. Perhaps this conclusion is not very surprising, since solar cell measurements are made for the purpose of predicting performance in sunlight.

Although the results presented above are for crystalline silicon, the conclusions are likely to hold for cells made on other materials.

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