Concentrator Cell Efficiency Measurement Errors Caused by Unfiltered Xenon Flash Solar Simulators

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Abstract. In this paper, we examine the effects of increased irradiance into one subcell of triple-absorber concentrator solar cells during efficiency measurements. This situation can easily occur when unfiltered xenon flash solar simulators are used for illumination. We demonstrate how excess irradiance into bottom subcells causes artificially increased fill factors, and that commonly used measurement procedures are unable to account for any excess irradiance. The effect always results in efficiency values that are too high.

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INTRODUCTION

It has been realized for many years that accurate efficiency measurements of series-connected multijunction solar cells requires the incident spectral irradiance be such that the photocurrents of the component subcells correspond to those that would be produced by the reference spectrum [1–6]. Spectral content affects not only the short-circuit current (I_{sc}) but also the open-circuit voltage (V_{oc}), fill factor (*FF*), and maximum power point (P_{max}) of these devices. Photocurrent balancing (or tuning) must be done with spectrally adjustable solar simulators.

In this paper, we compare measurements made with two simulators manufactured by Spectrolab, Inc.—a High-Intensity Pulsed Solar Simulator (HIPSS) and a new Tunable-HIPSS (T-HIPSS)—and demonstrate how the unfiltered-Xe HIPSS leads to significant artificial increases in the efficiency, especially in GaInAs-based triple-junction cells.

MEASUREMENT ANALYSIS

The instantaneous power efficiency of a photovoltaic (PV) device can be defined as:

$$\eta_{PV} \equiv \frac{P_{max}}{E_T \cdot A} \quad (1)$$

In Eq. 1, the power into the device is expressed as the product of total irradiance (E_T) and the device area (A). For standardized concentrator measurements, E_T is defined as the integral over all wavelengths of the direct-normal reference spectrum [7].

When measuring single-junction devices, E_T is determined from the I_{sc} of a calibrated reference cell (I_R), where C_R is the calibration constant under the reference spectrum, corrected for spectral mismatch, and M is the spectral mismatch factor [8]:

$$E_T = \frac{I_R}{C_R \cdot M} \quad (2)$$

Because the photocurrent in single-junction devices can normally be assumed to be equal to I_{sc}, the spectral irradiance during a performance measurement may differ from the reference spectrum if E_T is measured with Eq. 2.

For concentrator cell efficiency measurements, the reference cell method of Eq. 2 is generally not used to measure total irradiance. Instead, the I_{sc} of a cell under test is calibrated at 1-sun prior to testing under concentration, ideally using a spectrally adjustable simulator. Then, under concentration, the variation of I_{sc} versus E_T is assumed to be linear, and E_T can be determined from the I_{sc} ratio (also called the concentration ratio). Equation 2 becomes:

$$E_T = 1000\,\mathrm{Wm^{-2}}\,\frac{I_{SC}}{I_{1\times}} \quad (3)$$

By convention, 1000 $\mathrm{Wm^{-2}}$ is arbitrarily defined at the 1-sun total irradiance for standard concentrator measurements, even though the total irradiance of the direct-normal reference spectrum is 900 $\mathrm{Wm^{-2}}$.

An implicit assumption in Eq. 3 is that the spectral irradiance under concentration is equivalent to that of the 1-sun calibration. This paper documents how this assumption is invalid when unfiltered Xe lamps are used for efficiency measurements of multijunction concentrator devices.

Referring to the ideal equivalent-circuit model in Fig. 1, each subcell is represented by a current source equal to its photocurrent, in parallel with a diode. At open circuit, $I_{Load} = 0$ and all photocurrents flow through the diodes, forcing them into forward bias according to their diode characteristics. The cell voltage is then:

$$V_{Load} = V_{oc} = V_T + V_M + V_B \qquad (4)$$

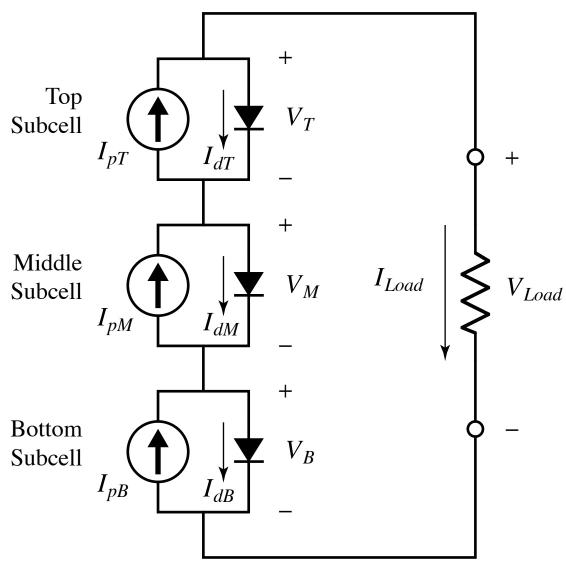

FIGURE 1. Simplified equivalent-circuit model of a series-connected triple-junction cell. Parasitic series and shunt resistances are neglected, and the interconnecting tunnel junctions are assumed to be ideal.

From solar cell theory, increasing the photocurrent in a p-n junction at 25°C increases V_{oc} according to Eq. 5 [9]:

$$\Delta V_{oc} = 25.7\text{mV} \cdot n \cdot \ln(R) \qquad (5)$$

Here, R is the photocurrent ratio and n is the diode quality factor. The increase is directly proportional to n and does not depend on the magnitude of the subcell V_{oc}. Thus, subcells with poor n factors will have larger errors. Also, according to Eq. 4, if two subcells have excess photocurrents, both will contribute to the V_{oc} error.

Next, assume the external load is such that $0 < I_{Load} < I_{sc}$. Because the same current must flow through each subcell:

$$I_{Load} = I_{pT} - I_{dT} = I_{pM} - I_{dM} = I_{pB} - I_{dB} \qquad (6)$$

The diode (or dark) currents are the familiar Shockley ideal diode equation [10]:

$$I_d = I_0 \left[\exp\left(\frac{qV}{nkT} \right) - 1 \right] \qquad (7)$$

In Eq. 6, one subcell will be operating such that its photocurrent and diode characteristic determine the current through the external load; this is known as the limiting subcell. Although it may be the subcell with the smallest photocurrent, it does not have to be.

Now consider what can occur when the irradiance into a non-limiting subcell is increased, thereby perturbing the photocurrent balance. First, I_{Load} does not increase even though more light is now entering the cell. Second, the operating point of the affected subcell changes because the extra photocurrent cannot flow through the external load; it can only flow through the subcell diode.

This increased diode current moves the operating point farther into forward bias, which increases the subcell voltage and increases the P_{max} and FF of the triple-junction cell. However, the measurement procedure cannot account for the excess irradiance because the I_{sc} in Eq. 3 does not change. Thus, the effect results in efficiency values that are always too high.

TRIPLE-JUNCTION CELL EFFICIENCY MEASUREMENTS

A Spectrolab HIPSS has been used at the National Renewable Energy Laboratory (NREL) for efficiency versus concentration measurements of III-V solar cells for a number of years. The HIPSS is a focused, long-arc Xe simulator with a 3-ms pulse duration, and has adjustable slits to vary the total irradiance [11]. Because it has no spectral filtering, the prominent Xe emission lines between 800 and 1050 nm are not suppressed, although the spectrum can be shifted to shorter wavelengths by changing the voltage setpoint of the flash on the power supply.

Figure 2 is an example HIPSS measurement for a GaInP/GaAs/Ge triple-junction cell. The flash voltage was selected to balance the top and middle subcell photocurrents, whereas the 0.7-eV bottom subcell photocurrent was neglected [6,11]. Thus, the Xe emission lines below the GaAs band edge at 900 nm were assumed to not adversely affect results.

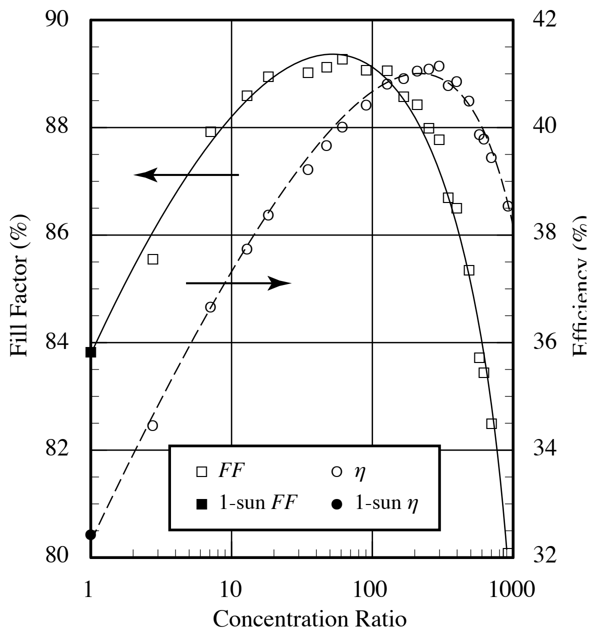

FIGURE 2. Fill factor and efficiency versus concentration ratio for a 41%-efficient GaInP/GaAs/Ge triple-junction cell (HIPSS data). The 1× data points were measured separately in a spectrally adjustable continuous simulator; concentration was calculated as the ratio of the HIPSS I_{sc} to the 1-sun I_{sc}.

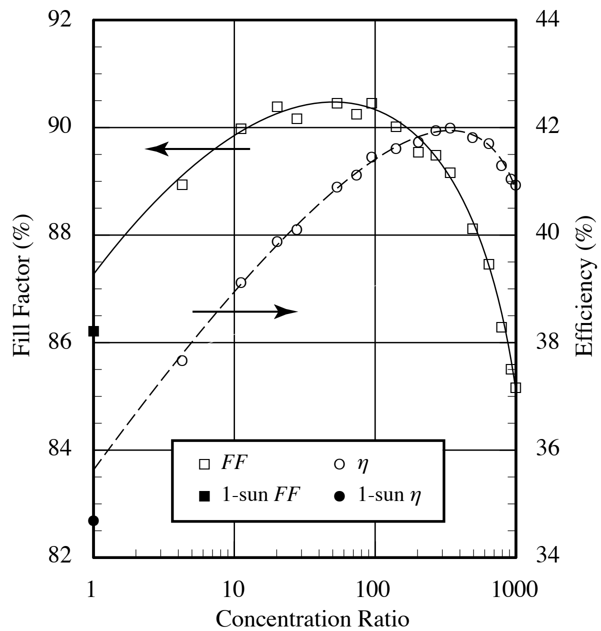

FIGURE 3. Fill factor and efficiency versus concentration ratio for a GaInP/GaAs/GaInAs triple-junction cell, measured with the same procedure as that of Fig. 2 (HIPSS data).

Next, this same procedure was applied to a GaInP/GaAs/GaInAs triple-junction cell in which the 1.0-eV bottom subcell photocurrent was considerably smaller as compared with the top and middle subcells. These data are shown in Fig. 3, which show ~1 percentage point discontinuities when the trends in the *FF* and efficiency (η) are extrapolated down to 1×. Similar measurements of other devices have shown considerably larger discontinuities; *FF* offsets as high as 4 percentage points and fill factors as high as 93%–94% under concentration have been observed.

A Spectrolab Model 460 T-HIPSS has replaced the HIPSS for all standard concentrator cell efficiency measurements at NREL. The flash characteristics of the T-HIPSS are similar to those of the HIPSS, but 14 discrete thin-film dielectric mirrors replace the parabolic reflectors. Spectral adjustment is accomplished with computer-controlled shutters that cover the mirrors, thus giving the ability to subtract light in six different wavelength bands [12].

Thus, it is now possible to correctly balance all three photocurrents under concentration. In Fig. 4, the same GaInP/GaAs/GaInAs triple-junction cell of Fig. 3 was measured in the T-HIPSS and the results plotted versus concentration. Notice that the trends agree much more closely with the 1-sun data, without the discontinuities.

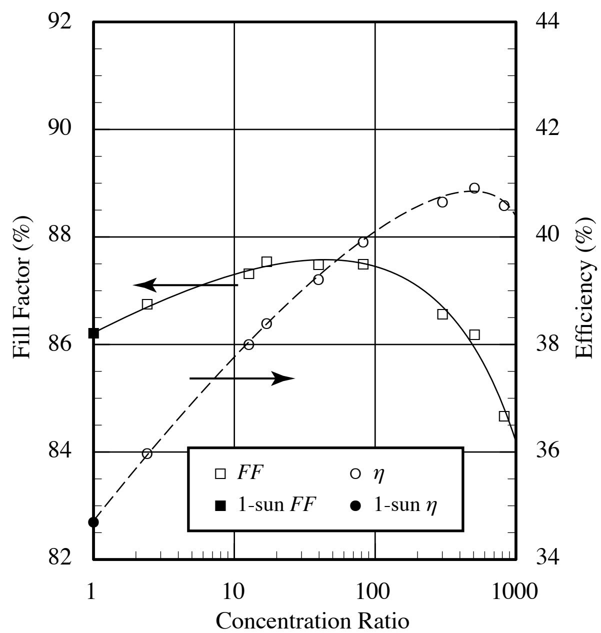

FIGURE 4. Fill factor and efficiency versus concentration ratio for the same GaInP/GaAs/GaInAs triple-junction cell shown in Fig. 3 (T-HIPSS data). Subcell photocurrents were correctly adjusted for all three subcells.

EXCESS SUBCELL PHOTOCURRENTS

Several experiments were performed to estimate the magnitudes of the excess bottom subcell photocurrents caused by the spectral irradiance of the HIPSS. Using calibrated isotype reference cells that correspond to the individual subcells, the excess photocurrent in the HIPSS can be estimated if the spectral mismatch factors are assumed to be unity [1,2,4]. In Fig. 5, the I_{sc} of three isotype cells were measured as the flash voltage was varied, and from these the photocurrent ratios were calculated. A voltage at which the top and middle subcells are balanced is evident, 372, and at this voltage the bottom subcell ratios indicate it receives 34% extra irradiance.

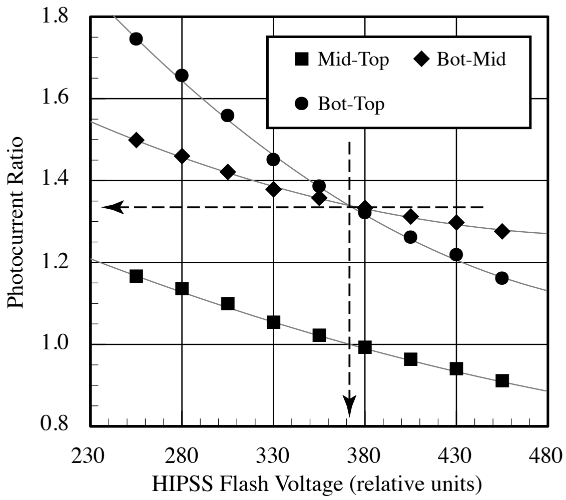

FIGURE 5. Subcell photocurrent ratios versus HIPSS flash voltage. The vertical arrow indicates where the middle-top ratio is 1.00 (372), and the horizontal arrow indicates the photocurrent ratios for the bottom subcell (1.34).

Further, Fig. 5 shows that regardless of the middle-top ratio, the bottom ratios are always considerably higher. Thus, there is no way to correctly adjust the HIPSS spectral irradiance without extra filtering at wavelengths greater than 900 nm.

We have also verified that excess 1-eV bottom subcell photocurrents cause artificial increases in *FF* with carefully controlled experiments in a 1-sun multisource simulator [12,13]. The irradiance into the bottom subcell of a GaInP/GaAs/GaInAs triple-junction cell was varied from the balanced condition while the middle-top photocurrent ratio was held at 1.00. These data are plotted in Fig. 6, which shows the *FF* increasing from 84% to 87% as the bottom subcell irradiance is increased by 40%. Also, the I_{sc} is nearly constant, which indicates either the top or the middle subcell is limiting the current through the triple-junction cell stack, as expected from Eq. 6 in the simple model used above.

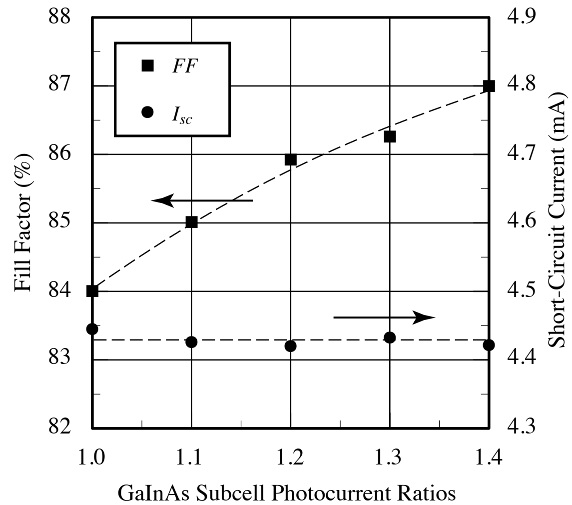

FIGURE 6. *FF* and I_{sc} for a GaInP/GaAs/GaInAs triple-junction cell vs GaInAs bottom subcell photocurrent ratios, measured in a 1-sun spectrally adjustable simulator [12].

Although not shown in Fig. 6, the triple-junction cell V_{oc} increased logarithmically with the bottom subcell photocurrent, and was 10 mV higher with 40% excess irradiance. Using ΔV_{oc} = 10 mV and R = 1.4 in Eq. 5 gives a diode quality factor of 1.156. Alternatively, a logarithmic fit of the V_{oc} versus R data gave an n = 1.121.

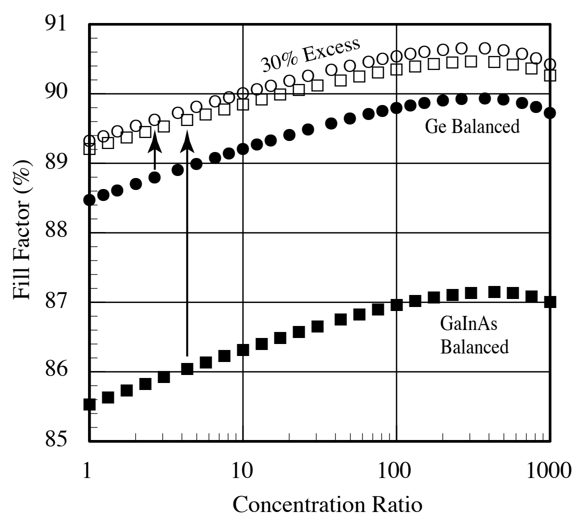

FIGURE 7. Modeled *FF* versus concentration ratio for two triple-junction cell designs, one with a Ge bottom subcell and the other with a 1-eV GaInAs bottom subcell. The solid points represent the fill factors with balanced photocurrents, while the open points have 30% excess bottom subcell photocurrents.

To test the hypothesis that excess bottom subcell photocurrents on the order of 30%–40% in magnitude can cause increases in *FF*, we used a numeric model to generate *FF* versus concentration for triple-junction cells with GaInAs- and Ge-based bottom subcells. The top and middle subcells were GaInP and GaAs with $n = 1.00$, and $n = 2.00$ for the bottom subcells in both cases. A series resistance was chosen to simulate a reasonable roll-off at high concentration. These calculations are plotted in Fig. 7.

The Ge design shows an offset of ~1 percentage point, while the GaInAs design increases by 3.5 percentage points—an error in the *FF* of more than 4% absolute. These calculations agree with the observations in Figs. 2 and 3, although the assumption of $n = 2.00$ for the bottom subcells could be high in the real devices measured here.

CONCLUSIONS

When compared with the direct-normal reference spectrum, the spectral content of unfiltered Xe flash lamps for infrared (IR) wavelengths greater than 900 nm is too high due to the Xe emission lines. In the past, measurement of GaInP/GaAs/Ge concentrator triple-junction cells has been possible using such simulators because the Ge bottom photocurrents were much higher than those of the top and middle subcells.

Newer triple-junction cell designs with bottom subcells that have wider bandgaps are much more sensitive to excess IR irradiance. When illuminated with a raw Xe spectrum, the internal diode characteristics of newer high-efficiency GaInAs-based cells produce current-voltage curves with inflated fill factors and results in measured efficiency values that are always too high.

This error can be avoided with proper spectrally adjustable measurement systems, such as the Spectrolab T-HIPSS.

A good rule-of-thumb based on our work is that any concentrator SRC efficiency measurement of a triple-junction cell should be flagged and suspected of having excess bottom-subcell irradiance if: the subcell photocurrents are comparable in magnitude, it uses unfiltered Xe simulator illumination, and the fill factor exceeds 88% to 89% at high concentration.

Although the error has been identified in GaInP/GaAs/GaInAs triple-junction cells measured with unfiltered Xe-arc lamps, it should be emphasized that similar errors can arise whenever the photocurrent in a single subcell is artificially increased, regardless of the subcell's bandgap. Increasing the photocurrent in a GaAs middle cell, for example, will also increase the measured efficiency.

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