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Procedures at NREL for Evaluating Multijunction Concentrator Cells

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ABSTRACT

The procedures for evaluating the performance of multijunction-concentrator cells at the National Renewable Energy Laboratory are described. The accurate measurement of the performance of multijunction cells requires accurate relative-quantum-efficiency-measurements, "matched" reference cells, and a spectrally adjustable solar simulator.

1. Introduction

The procedures for evaluating multijunction cells are a generalization of single junction measurement procedures developed in 1985 [1]. The procedures were first documented in 1986 [2] and adopted by various groups [3-5]. The procedures involve adjusting the spectrum of the solar simulator until each junction is operating at its correct photocurrent. This is accomplished for an n-junction solar cell by satisfying the following set of equations

$$I^{R_1,S} = \frac{I^{R_1,R}}{M_1}$$
$$I^{R_2,S} = \frac{I^{R_2,R}}{M_2}$$
$$\vdots \qquad (1)$$
$$I^{R_n,S} = \frac{I^{R_n,R}}{M_n}$$

where I is the short-circuit current and M is the spectral mismatch. The superscript R_n,R denotes the reference cell for junction n under the reference spectrum while the superscript R_n,S denotes the reference cell for junction n under the simulator spectrum.

The spectral mismatch or correction factor M_n for junction n is given by

$$M_n = \frac{\int_{\lambda_1}^{\lambda_2} E_s(\lambda) * S_{tn}(\lambda) \mathrm{d}\lambda}{\int_{\lambda_3}^{\lambda_4} E_s(\lambda) * S_{rn}(\lambda) \mathrm{d}\lambda} * \frac{\int_{\lambda_3}^{\lambda_4} E_{ref}(\lambda) * S_{rn}(\lambda) \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_{ref}(\lambda) * S_{tn}(\lambda) \mathrm{d}\lambda} \qquad (2)$$

where $S_{tn}(\lambda)$ is the spectral response of junction n and $S_{rn}(\lambda)$ is the spectral response of the reference cell for junction n. The reference spectral irradiance is $E_{ref}(\lambda)$ and the simulator spectral irradiance is $E_s(\lambda)$. The spectral response for each junction of a multijunction device is determined by using filtered constant-light bias to turn on all of the junctions not being measured and illuminating the cell with chopped monochromatic light. Applying a voltage bias may also be required for multijunction devices with voltage-dependent quantum efficiency such as amorphous silicon. This is generally accomplished by applying a forward bias until the responsivity is a maximum. For two identical junctions in series this would be one half of the open-circuit voltage. This allows the cell being measured to operate at 0 volts while the junction not being measured is operating near its open-circuit voltage.

These procedures have been followed since 1987 for 1-sun multijunction cells. Ideally these procedures should be followed for measurements under concentrated light. The spectrum of NREL's High Intensity Pulsed Solar Simulator (HIPSS) could be altered by placing filters close to the lamps but this has not been done yet. Currently, procedures determine the concentration ratio from the 1-sun short-circuit current. A separate set of measurements are performed to determine if the current is linear with total irradiance. The 1-sun multi-source simulator; and concentrator results are compared to determine if there is a large difference in the fill factor. A difference in the fill factor could indicate that a different junction is current limiting under the HIPSS light than under the standard spectrum.

2. Example

The spectral responsivity for the individual junctions for the GaInP/GaAs/Ge triple-junction concentrator cell is shown in Figure 1. The cell was developed and grown at Spectrolab and processed at NREL.

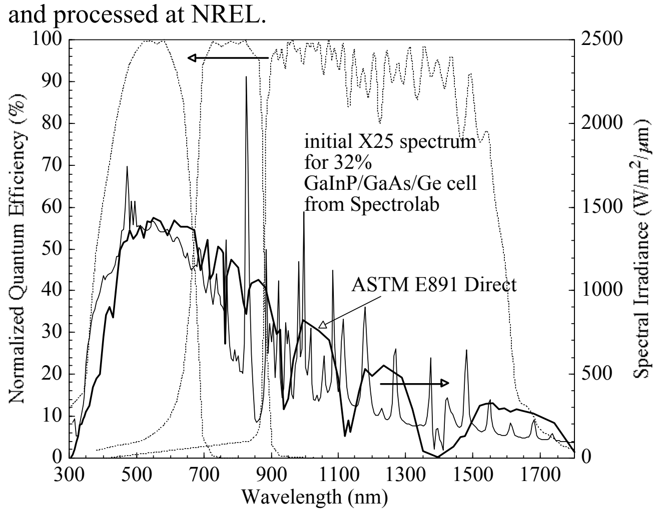

Figure 1. Spectrolab / NREL GaInP/GaAs/Ge triple-junction concentrator showing the normalized quantum efficiency for each junction, the direct-reference spectrum and the initial Spectrolab X25 spectrum.

Primary reference cells with an uncertainty of ±1% were available for the top and middle junction and a secondary reference cell of GaAs filtered Ge was calibrated for the bottom junction with an uncertainty of ±5%. The spectrum of NREL's Spectrolab X25 solar simulator was adjusted until the three-junctions' photocurrent was within ±1% of their calibrated value. The filtering of the X25 solar simulator was complicated by a lack of appropriate filters for the bottom junction. Ideally the filters should allow light for only one of the three junctions to pass through, allowing independent adjustment of the light to each junction. In reality, the filter's transmissions overlapped and, because of inadequate filters (Figure 2), the simulator could only achieve 750 W/m^2 without adversely affecting the spatial uniformity. Figure 2 shows the final filters used for the 32% for the cell in Figure 1.

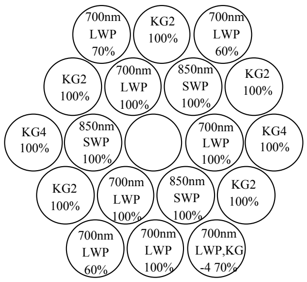

Figure 2. Position of the filters placed in front of the Spectrolab X25 solar for the GaInP/GaAs/Ge triple-junction cell.

Once the nominal 1-sun characteristics under the multi-source X25 are established, the sample is taken to the HIPSS and measured as a function of concentration as shown in Figure 3. The linearity of I_{sc} with total irradiance was

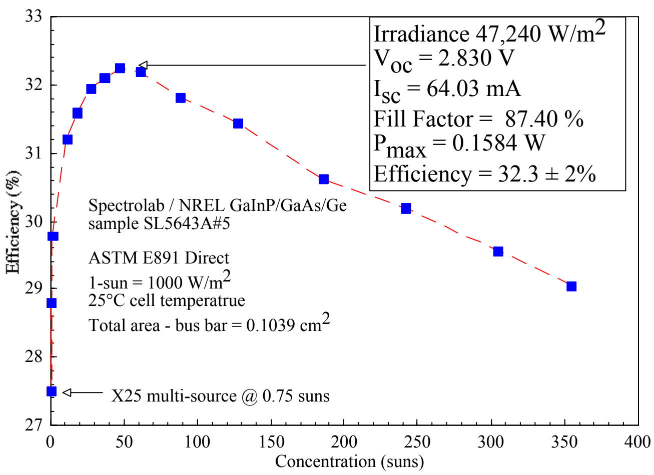

Figure 3. Efficiency *vs.* concentration assuming linearity for the cell described in Figures 1 and 2.

determined by measuring I_{sc} as a function of attenuation and plotting the ratio as a function of I_{sc}. The intensity was changed by adjusting apertures close to the lamp and by changing the lamp voltage. This maps the slope of I_{sc} *vs.* irradiance and is constant for linear devices. Figure 4 illustrates that, within experimental error, the slope is zero.

3. Summary

The procedures at NREL for evaluating the performance of multi-junction cells have been presented. Because of the urgent need to determine the spectral sensitivity of multi-junction devices over the period of a standard day, procedures to more rapidly determine the performance under varying spectral conditions are under development. The spectrum of the HIPSS must be made adjustable to properly evaluate the spectral sensitivity of concentrator cells. This has not been a major problem in the past because the current-limiting junction has been the same under the HIPSS and standard spectrum. The HIPSS must be able to measure irradiance directly so linearity assumptions and checks are not needed. Finally, the proper way to determine the linearity of a device is to measure its absolute spectral responsivity over the irradiance range of

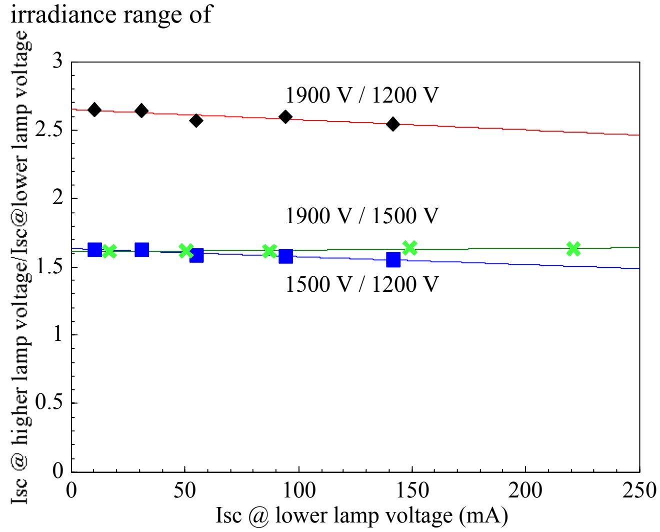

Figure 4. Variation in the slope as a function of current for the cell in Figure 3. showing linear behavior within experimental error.

interest. This is because simulator-based measurements, as a function of total irradiance are a function of the spectrum of the solar simulator that may not have the same functional dependence as the reference spectrum.

4. Acknowledgement

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