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Preprint

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*Presented at the 2012 IEEE Photovoltaic Specialists Conference
Austin, Texas
June 3–8, 2012*

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Conference Paper
NREL/CP-5200-54134
June 2012

Contract No. DE-AC36-08GO28308

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Algorithm for Building a Spectrum for NREL's One-Sun Multi-Source Simulator

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Abstract — Historically, the tools used at NREL to compensate for the difference between a reference spectrum and a simulator spectrum have been well-matched reference cells and the application of a calculated spectral mismatch correction factor, M . This paper describes the algorithm for adjusting the spectrum of a 9-channel fiber-optic-based solar simulator with a uniform beam size of 9 cm square at 1-sun. The combination of this algorithm and the One-Sun Multi-Source Simulator (OSMSS) hardware reduces NREL's current vs. voltage measurement time for a typical three-junction device from man-days to man-minutes. These time savings may be significantly greater for devices with more junctions.

Index Terms — calibration, multijunction, solar simulation, multisource simulator, spectral mismatch.

I. INTRODUCTION

The goal of a solar simulator and its data acquisition system is to determine the performance of a photovoltaic (PV) device under a desired reference spectrum. However, no simulator is perfect, not even the sun, because they all deviate from idealized reference spectra. For a single-junction device, the spectral mismatch correction factor indicates a change in the reference cell's calibration value under the simulator spectrum such that the test device will perform as it would under the reference spectrum [1]. This change in the reference cell's one-sun short-circuit current, I_{sc} , is achieved by changing the simulator's total irradiance, as indicated by the spectral mismatch correction factor, while leaving the shape of the normalized irradiance unchanged. This can be done by simply moving the simulator lamp closer or further from the test stage, or using screens or irises.

The situation is more complicated for multijunction devices because each of the n junctions requires its own matched reference cell and will yield its own, different, spectral mismatch correction factor. It is not adequate to simply change the simulator's total irradiance because each junction requires a different total irradiance change. Consequently, the simulator spectrum's shape, as well as its total irradiance, must be modified by the application of optical filters. Under the historical NREL procedures [2], this has been a non-intuitive iterative process that required repeated optical filter application adjustments, I_{sc} measurements for n reference cells matched to n junctions, simulator spectrum measurement, and recalculation of the n spectral mismatch correction factors. In practice, this procedure could take more than a man-day of

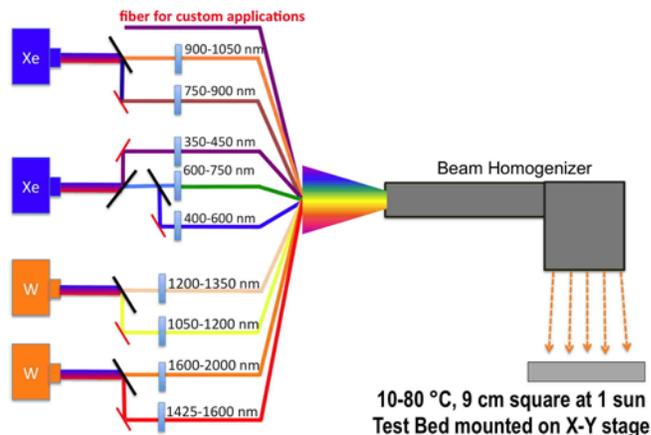


Fig. 1. One-sun multisource solar simulator. The wavelength regions for the nine fibers were chosen to correspond to likely multijunction structures.

effort for a typical three-junction device using NREL's Spectrolab X25 solar simulator.

This procedure has been greatly simplified with the advent of NREL's One-Sun Multi-Source Simulator (OSMSS), shown in Figs. 1 and 2. The OSMSS has three primary features that make this possible: nine largely (but not completely) non-overlapping spectral bands that are independently adjustable via computer from zero to 150% of the irradiance in the corresponding reference spectrum bands, a very fast spectroradiometer, and a spectrum-adjustment algorithm that relies solely on the quantum efficiencies of the n test device junctions to build the shape of the simulator spectrum (without the use of n corresponding reference cells and spectral mismatch correction factors). Performance measurements with the OSMSS take several man-minutes, instead of man-days.

This paper is primarily concerned with a comparison of the spectral adjustment algorithm historically used at NREL and the new algorithm used with the OSMSS.

II. SPECTRAL MISMATCH CORRECTION, M_i , v/s. JUNCTION CURRENT RATIO, R_{ij}

Consider a normalized simulator spectrum flux, $\Phi_{sim}(\lambda)$, and normalized quantum efficiency for test device junction i , $Q_i(\lambda)$, and a corresponding reference cell with normalized quantum efficiency, $Q_{ref,i}(\lambda)$, which is known to yield a short-

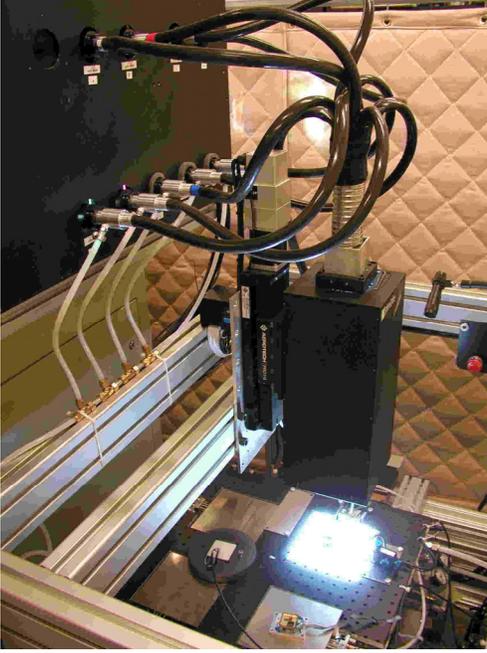


Fig. 2. Photograph of one-sun multisource solar simulator.

circuit current of $I_{Ref\ i, Ref\ spec}$ under the desired reference spectrum flux, $\Phi_{Ref}(\lambda)$. Then the test device junction i will yield its reference spectrum short-circuit current $I_{test\ i, Ref\ spec}$ under the simulator spectrum when the corresponding reference cell yields a current given by

$$I_{Ref, Sim\ spec} = \frac{I_{Ref, Ref\ spec}}{M_i} \quad (1)$$

where M_i is the spectral mismatch correction factor for the i^{th} junction and is given by

$$M_i = \frac{\int \Phi_{Ref}(\lambda) Q_{Ref, i}(\lambda) d\lambda}{\int \Phi_{Sim}(\lambda) Q_{Ref, i}(\lambda) d\lambda} \times \frac{\int \Phi_{Sim}(\lambda) Q_i(\lambda) d\lambda}{\int \Phi_{Ref}(\lambda) Q_i(\lambda) d\lambda} \quad (2)$$

A simulator spectrum that best reproduces the effect of the desired reference spectrum must satisfy Eq. (1) for all i . So, from Eq. (1), for any two junctions, i and j ,

$$\frac{I_{Ref, Sim\ spec}}{I_{Ref, Sim\ spec}} = \frac{I_{Ref, Ref\ spec}}{I_{Ref, Ref\ spec}} \times \frac{M_j}{M_i} \quad (3)$$

The goal of the historical NREL iterative process mentioned above is to find a simulator spectrum, $\Phi_{sim}(\lambda)$, that satisfies Eq. (3) for all possible combinations of i and j .

Now consider the short-circuit current for the isolated i^{th} junction of an n-junction device under some spectrum flux,

$$I_{i, flux} = \int \Phi(\lambda) Q(\lambda) d\lambda \quad (4)$$

The ratios of currents for isolated junctions i and j under a simulator spectrum that best reproduces the effect of a desired reference spectrum should be the same as the ratio of currents under that desired reference spectrum. So, from Eq. (4),

$$\frac{\int \Phi_{Ref}(\lambda) Q_i(\lambda) d\lambda}{\int \Phi_{Ref}(\lambda) Q_j(\lambda) d\lambda} = \frac{\int \Phi_{Sim}(\lambda) Q_i(\lambda) d\lambda}{\int \Phi_{Sim}(\lambda) Q_j(\lambda) d\lambda} \quad (5)$$

We define the junction current ratio, R_{ij} , as

$$R_{ij} = \frac{\int \Phi_{Ref}(\lambda) Q_i(\lambda) d\lambda}{\int \Phi_{Ref}(\lambda) Q_j(\lambda) d\lambda} \times \frac{\int \Phi_{Sim}(\lambda) Q_j(\lambda) d\lambda}{\int \Phi_{Sim}(\lambda) Q_i(\lambda) d\lambda} \quad (6)$$

From Eqs. (5) and (6), an ideal simulator spectrum would be defined by

$$R_{ij} = 1 \quad \forall i, j \quad (7)$$

The OSMSS spectrum consists of a linear combination of nine largely non-overlapping spectra $\Phi_{sim, k}$. The goal of the OSMSS spectrum-building algorithm is to find a linear combination of the $\Phi_{sim, k}$ that satisfies Eq. (7). Unlike the spectral mismatch correction method, the junction current ratio method does not use any reference cells to find the best spectrum shape. In practice at NREL, an automated iterative process to satisfy Eq. (7) occurs after building a simulator spectrum that matches the reference spectrum irradiance in nine wavelength bands. Consequently, the built spectrum tends to be a close match to the reference spectrum.

III. HARDWARE

The OSMSS consists of two 1500-W Xe lamps and two 750-W tungsten lamps whose spectra are divided into nine wavelength bands (see Fig. 1). The light from each band is coupled to a light integrator box (nominally about 18 cm above the stage) via large optical fiber bundles. The total flux in each of the simulator bands is adjustable from 0% to about 150% of the AM1.5 direct spectrum in about 0.1% increments through variable apertures at the entrance to each fiber bundle. Figure 3 shows a typical built spectrum and the nine individual spectra from the nine channels. The light integrator box has a 10-cm vertical motion range to allow for adjustment of the total irradiance of the built spectrum on the stage.

The stage has a 25-cm range of motion in the XY plane so reference cells, test devices, and spectral sensors can be moved in and out of the built spectrum. The movable stage has four separately adjustable, temperature-controlled (10°–80°C) vacuum chucks.

A fast spectroradiometer provides rapid feedback for the calculation of R_{ij} during the spectrum-building process. A large assortment of primary calibrated reference cells is available for the magnitude adjustment of the built spectrum shape. NREL standard op-amp circuits hold reference and monitor cells at I_{sc} at all times.

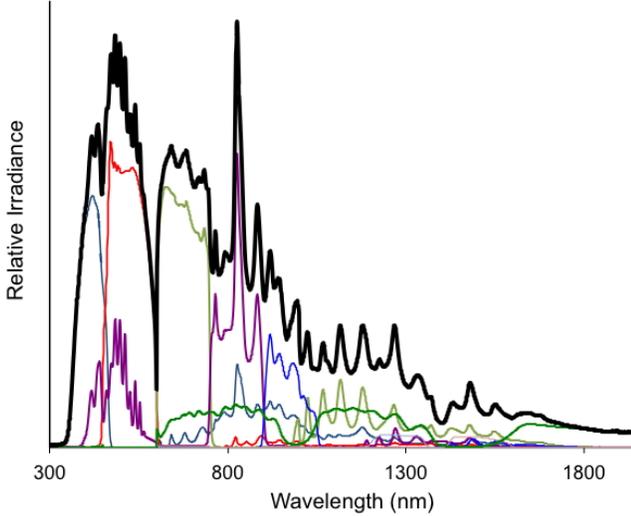


Fig. 3. OSMSS simulator spectrum and the nine individual channel spectra.

IV. BUILDING THE SPECTRUM

The procedure for building the spectrum consists of three main steps: an approximation of the reference spectrum shape, an iterative process to adjust the combination of simulator spectra until $|R_{ij} - I|$ is less than some threshold (usually 0.01), and adjustment of the magnitude of the overall combined spectra so that the test device yields the same current as it would under the reference spectrum.

Step 1.

The variable aperture position vs. percent of maximum irradiance is measured and recorded every several months or when any major optical change has been made to the system. The first step to build the spectrum shape is to use these data to adjust each simulator band to near its 50% maximum irradiance and measure its irradiance with all other bands set to zero. A linear combination of these nine separate spectra is built such that the relative flux in each nominal wavelength band matches the desired reference spectrum.

Step 2.

R_{ij} is calculated from Eq. (6) for each junction combination with an iterative process to adjust the m channel fluxes, Φ_k , (for the OSMSS, $m=9$) to satisfy Eq. (7), within the desired threshold. At NREL, we have used two different methods to accomplish this task. Both methods follow a “model,” “build,” and “measure” iterative process. The difference between the two methods is in the modeling step.

The first method has successfully built an appropriate simulator spectrum for every two- and three-junction device

tested (III-V, a-Si, organic), but takes an inordinate amount of time to converge for a four-junction device. Consider a three-junction device with three possible R_{ij} (R_{12} , R_{13} , and R_{23}) and a simulator with multiple channel fluxes, Φ_k . By restricting the simulator spectral shape adjustment to variations in only three channel fluxes, the theoretical proper adjustments of those fluxes, $\Delta\Phi_k$, can then be modeled by

$$\left[\frac{\partial R_{ij}}{\partial \Phi_k} \right] [\Delta\Phi_k] = [1 - R_{ij}] \quad (8)$$

For a three-junction cell, Eq. (8) expands to

$$\begin{bmatrix} \frac{\partial R_{12}}{\partial \Phi_1} & \frac{\partial R_{12}}{\partial \Phi_2} & \frac{\partial R_{12}}{\partial \Phi_3} \\ \frac{\partial R_{13}}{\partial \Phi_1} & \frac{\partial R_{13}}{\partial \Phi_2} & \frac{\partial R_{13}}{\partial \Phi_3} \\ \frac{\partial R_{23}}{\partial \Phi_1} & \frac{\partial R_{23}}{\partial \Phi_2} & \frac{\partial R_{23}}{\partial \Phi_3} \end{bmatrix} \begin{bmatrix} \Delta\Phi_1 \\ \Delta\Phi_2 \\ \Delta\Phi_3 \end{bmatrix} = \begin{bmatrix} 1 - R_{12} \\ 1 - R_{13} \\ 1 - R_{23} \end{bmatrix} \quad (9)$$

There are $\binom{m}{n}$ possible solution sets for the $\binom{m}{n}$ possible combinations of sets of linear equations represented by Eq. (8) or Eq. (9). A three-junction device ($n=3$) with a nine-channel simulator ($m=9$) will have 84 possible combinations and solution sets. Some solution sets can be eliminated because they dictate irradiances beyond the range of one or more of the chosen bands. Of those that remain, the best is chosen as the one that minimizes the difference with the reference spectrum as given in (10)

$$\min \int \left(\frac{\sum_k (\Phi_k(\lambda) + \Delta\Phi_k(\lambda))}{\sum_k \int (\Phi_k(\lambda) + \Delta\Phi_k(\lambda)) d\lambda} - \frac{\Phi_{ref}(\lambda)}{\int \Phi_{ref} d\lambda} \right)^2 d\lambda \quad (10)$$

A new simulator spectrum $\Phi_{sim,n+1}$ is created by adjusting previous simulator spectrum, $\Phi_{sim,n}$ according to Eq. (11), where the modeled $\Delta\Phi_k$ values are built by referencing the variable aperture position vs. percent irradiance data.

$$\Phi_{sim,n+1} = \Phi_{sim,n} + \sum_k \Delta\Phi_k \quad (11)$$

The total simulator spectrum is now measured and the R_{ij} values are recalculated. In about 50% of cases for two- and three-junction devices, the threshold for $|R_{ij} - I|$ is achieved with a single iteration of (9) and (10). If not, the process can be repeated until $|R_{ij} - I|$ is less than the desired threshold.

The second modeling method uses a search routine that is less elegant but more effective for devices with more than three junctions. Let $P_{n,k}$ be the percent of full irradiance for simulator band k . Then find $P_{n+1,k}$ such that

$$\sum_{(ij)} \left| R_{(ij)} + \frac{\partial R_{(ij)}}{\partial \Phi_k} \left(\frac{P_{n+1,k} - P_{n,k}}{P_{n,k}} \right) - 1 \right| \quad (12)$$

is minimized. In this way, each simulator band can be treated separately and sequentially in search of a satisfactory solution. Conceptually, in two dimensions (a two-band simulator), repeatedly minimizing (12) for each channel would be like following the path in Fig. 4.

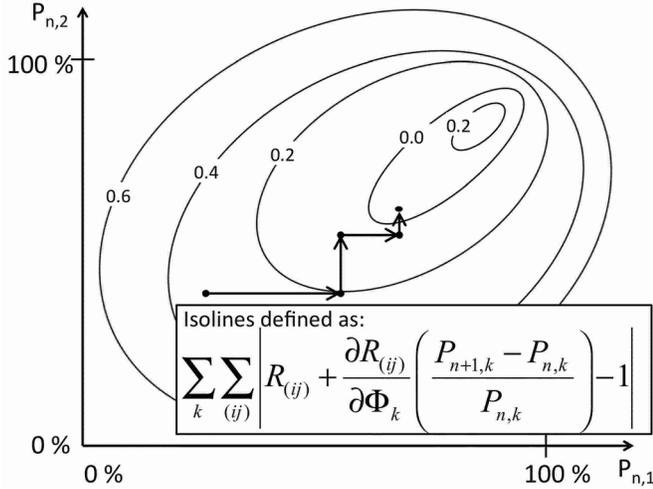


Fig. 4. Conceptual illustration of the second spectral modeling method obtained by minimizing (12) for two channels.

After each iteration of minimization of (12), the total simulator spectrum is remeasured and the R_{ij} s are recalculated. This method usually takes several iterations to converge because only one simulator band is changed at a time, and so, it takes longer for two- and three-junction devices. However, it has converged nicely for four- and six-junction devices.

Step 3.

Both step 2 spectrum modeling methods yield a simulator spectrum with the correct shape, but not necessarily the correct total irradiance. The correct total irradiance is set with the application of a single spectral mismatch correction factor for one test device junction and one reference cell. In practice, this entails an adjustment of the distance between the light integrating box and the test device until a reference cell current matches the current given by Eq. (1).

Several test devices have been measured on both systems. Figure 5 compares the spectrum built by the OSMSS for a three-junction device using the junction current ratio method and the ASTM G173-03 (AM1.5 direct) spectrum [3]. Figure 6 shows the resulting current vs. voltage for a typical triple-junction device where the photocurrents for each junction were within 1% of their value under standard 1-sun concentrator reference conditions. The performance of the

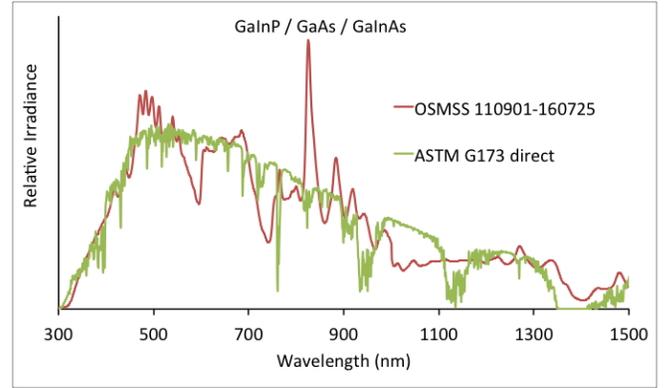


Fig. 5. Reference spectrum and simulator-built spectrum.

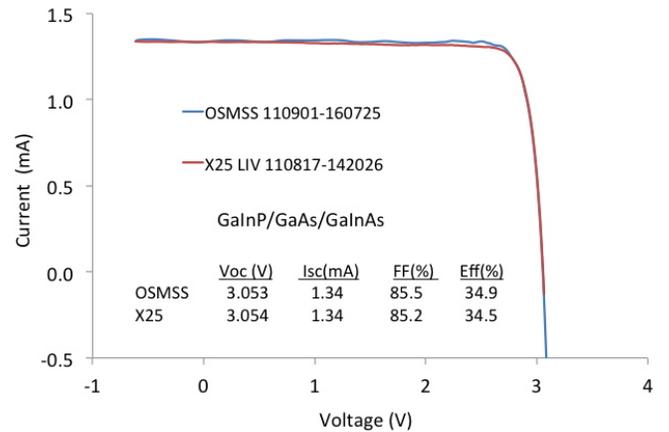


Fig. 6. Current vs. voltage for a triple-junction, high-efficiency cell for two spectrally adjustable solar simulators under standard reference conditions of 25°C, 1000 Wm⁻², ASTM G173 global [3].

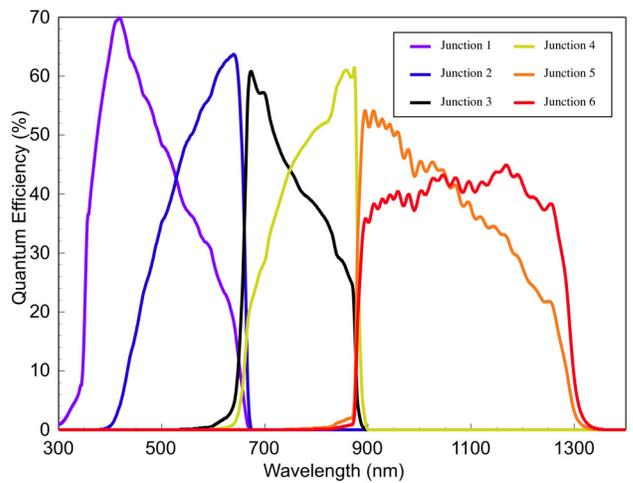


Fig. 7. Estimated quantum efficiencies for each of the six junctions in a six-junction cell.

VI. CONCLUSION

The OSMSS hardware, combined with the algorithm described here, reduces NREL's one-sun current vs. voltage measurement time for a typical three-junction device from man-days to man-minutes. This opens a new realm of research possibilities.

The time constraint imposed by the old hardware and procedures put a practical limitation on the number of reference spectra under which a cell could be measured (typically AM1.5 global and/or AM1.5 direct). With the new hardware and procedures, it is possible to measure a cell under multiple spectra that are representative of various locations, seasons, times of day, and weather. It may be possible to predict energy production for a typical meteorological year in a few hours in the laboratory, rather than collecting data for a year in the field.

In theory, it was possible to measure the current vs. voltage of a device with greater than three junctions using NREL's historic procedures, but the practical limitations made this a daunting prospect. After decades of measuring the performance of multijunction devices, no attempt was ever made to measure the current vs. voltage of any devices with four or more junctions. The OSMSS has now successfully measured a four-junction and six-junction device.

ACKNOWLEDGEMENT

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory. The use of the 6-junction cell provided by Solar Junction is acknowledged. The 3-junction inverted metamorphic cell was fabricated at NREL by the III-V team.

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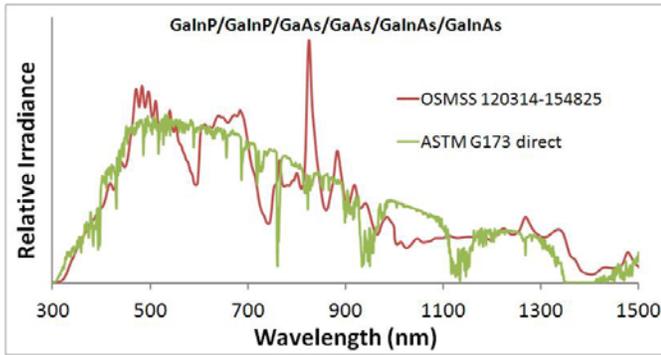


Fig. 8 Composite spectrum used in measuring the six junction cell.

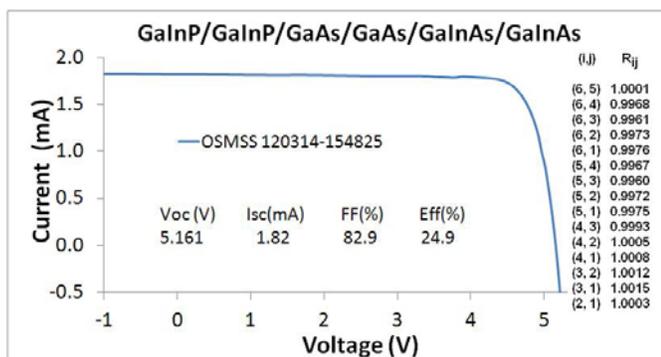


Fig. 9 Current versus voltage for a six junction high efficiency cell under standard reference conditions of 25 °C, 1000 Wm⁻², ASTM G173 global [3].

algorithm was challenged for a six-junction cell with three bandgaps, as shown in Figs. 7 thru 9. The algorithm adjusted the spectrum so that all six junctions were within 1% of their current under reference conditions assuming that there was no error in the six quantum efficiencies or measured spectrum.

V. FUTURE SPEED IMPROVEMENT

The first multijunction device of a measurement session typically takes about 8 minutes to build the required spectrum. Subsequent devices typically take 2 or 3 minutes (excluding probing time). This is because step 1 of the spectrum-building process takes the most time, but the result of step 1 can be used for subsequent cell measurements. Step 2 takes about 1 minute per iteration.

Most of the time consumed in steps 1 and 2 of the spectrum-building process is used in moving the variable apertures. Current hardware limitations prevent these apertures from being adjusted simultaneously. When that limitation is overcome, measurement times should be reduced by more than 50%.