Device Characterization For Design Optimization Of 4 Junction Inverted Metamorphic Concentrator Solar Cells

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Abstract. Quantitative electroluminescence (EL) and luminescent coupling (LC) analysis, along with more conventional characterization techniques, are combined to completely characterize the subcell JV curves within a four-junction (4J) inverted metamorphic solar cell (IMM). The 4J performance under arbitrary spectral conditions can be predicted from these subcell JV curves. The internal radiative efficiency (IRE) of each junction has been determined as a function of current density from the external radiative efficiency using optical modeling, but this required the accurate determination of the individual junction current densities during the EL measurement as affected by LC. These measurement and analysis techniques can be applied to any multijunction solar cell. The 4J IMM solar cell used to illustrate these techniques showed excellent junction quality as exhibited by high IRE and a one-sun AM1.5D efficiency of 36.3%. This device operates up to 1000 suns without limitations due to any of the three tunnel junctions.

Keywords: 4-junction, concentrator solar cell, electroluminescence, luminescent coupling

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INTRODUCTION

The typical characterization of multijunction concentrator solar cells at some concentration under the AM1.5 direct spectrum at 25°C may be useful for a simple comparison between solar cells. But when the goal is the optimization of solar cell designs for energy yield under real-world conditions that continuously vary, measurements that characterize the physics of all subcomponents of the complex opto-electronic device that is a multijunction solar cell are required to predict the performance under arbitrary conditions. Each component of a monolithic multijunction solar cell can be affected by the growth and mere presence of the other subcomponents. For example, luminescent coupling transfers current from one junction to a subsequent junction depending on its light and voltage bias conditions. Therefore, it is important to characterize all subcomponents within a completed multijunction device.

Electroluminescence¹ (EL) and luminescent coupling² (LC) measurements and analyses of multijunction solar cells are powerful techniques to probe the individual junction voltage and photocurrent characteristics, and how they affect each other. Combining these techniques along with optical modeling can give a nearly complete picture of the multijunction solar cell performance under arbitrary conditions as well as characterize the primary metrics of junction quality³: external radiative efficiency (ERE) and internal radiative efficiency (IRE).

We have grown high-quality monolithic four-junction inverted metamorphic (4J IMM) solar cells with two metamorphic InGaAs junctions using two compositionally graded GaInP buffer layers and a metamorphic GaAsSb/GaInAs tunnel junction⁴ between these junctions. Inverted 4J solar cells are grown on GaAs substrates by atmospheric pressure metal organic vapor phase epitaxy and subsequently processed as described previously for 3J IMM solar cells⁵. Adjustable parameters of the design include bandgap through composition and ordering, absorber layer thickness, doping, optical structure such as antireflective coatings and back reflectors, and material quality. In this paper, we illustrate characterization using EL and LC measurements of a single 4J IMM solar cell that can be used to provide performance feedback to the design optimization using these adjustable parameters.

LUMINESCENT COUPLING

The amount of light incident on the 4J solar cell is quantified and varied on a spectrally adjustable solar simulator outfitted with a spectroradiometer and four monochromatic light emitting diode (LED) sources matched to the four junctions. A spectral mismatch correction⁶ is performed to quantify the concentration of light (suns relative to AM1.5 direct) on each
junction using external quantum efficiency (EQE) measurements corrected for LC effects, roughly matched reference cells, and the actual simulator spectrum. Complete current density-voltage measurements (JV) are collected at each spectral condition, as shown in figure 1, where the characteristic of reverse breakdown was observed whenever the 4th junction is limiting. The limiting photocurrent (plotted in figure 2) was therefore measured at a voltage bias of 2.8 V, which is between the maximum power point and the onset of reverse breakdown. The external photocurrent of each subcell and the LC parameters ($\eta_{i,i+1}$ and $\phi_i$) listed in table 1 were determined to fit the data as described previously for 3J solar cells. Sensitive determination of each LC parameter was promoted by choosing spectral conditions that 1) limit each junction, and 2) force LC between each pair of junctions to dominate the limiting photocurrent.

**ELECTROLUMINESCENCE**

The EL light emitted from each junction is quantified as the forward injection current density is varied in the dark. The emitted spectra shown in figure 3 were normalized by the spectroradiometer calibration to give units of photon flux / area / wavelength. The total external radiative flux from the $i$th junction in units of current density ($J_{i}^{em}$) is calculated within a geometric constant by integrating over each EL peak emission spectrum:

$$J_{i}^{em} = \int S_{i}(\lambda) \, d\lambda$$

where $S_{i}(\lambda)$ is the EL emission spectrum of the $i$th junction. By summing the subcell voltages at each EL measurement condition and fitting to the measured dark JV curve of the series-connected 4J device, the geometric constant is experimentally determined. Thus, the dark JV of each subcell $J_{i}^{em}$ vs. $V_i$ can be constructed as shown in figure 4. Previous literature assumed the injection current density of each subcell ($J_{i}^{inj}$) to be the experimentally measured injection current density of the overall series-connected tandem, but this is not strictly true in the presence of LC. Using the LC parameters determined in the previous section, we correct $J_{i}^{inj}$ for LC during the EL measurement as
TABLE 1. Subcell parameters extracted from LC and EL measurements (* AM1.5D conditions)

<table>
<thead>
<tr>
<th>Junction</th>
<th>Photocurrents (mA/cm²)</th>
<th>Coupling Parameters</th>
<th>Optical Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>External</td>
<td>Total</td>
<td>QE</td>
</tr>
<tr>
<td>GaInP</td>
<td>13.57</td>
<td>12.60</td>
<td>12.60</td>
</tr>
<tr>
<td>GaAs</td>
<td>13.32</td>
<td>12.70</td>
<td>12.70</td>
</tr>
<tr>
<td>InGaAs (1.0eV)</td>
<td>12.72</td>
<td>13.30</td>
<td>13.30</td>
</tr>
<tr>
<td>InGaAs (0.7eV)</td>
<td>12.45</td>
<td>13.10</td>
<td>13.17</td>
</tr>
</tbody>
</table>

FIGURE 4. 4J IMM subcell dark JV from EL with (filled red) and without (open black) LC correction.

FIGURE 5. ERE and IRE of each junction in 4J IMM.

shown in figure 4. LC can result in corrections to on the order of 2X for strong and cascading LC. The resulting correction to the subcell  is minimal (<10mV) due to the logarithmic nature of the JV curves, but calculation of the ERE, is strongly affected. Indeed, the IRE (discussed next) results in unphysical values greater than unity if the EL is not corrected for LC effects.

Optical modeling given accurate layer thicknesses and material constants allows a connection to be made between the internal and external radiative efficiency of the th junction

\[
\eta_i^{\text{int}} = \frac{\eta_i^{\text{ext}}}{P_i^{\text{esc}} + \eta_i^{\text{abs}} P_i^{\text{abs}}},
\]

where and are the average probabilities that an internally emitted photon either escapes out the front of the device or is reabsorbed within the junction respectively. We confirm the accuracy of the optical model, by accurately fitting the reflectance and EQE of each junction (not shown). The ERE and IRE of each junction are shown in figure 5. The IRE is the ultimate measure of junction quality, since a perfect junction with zero non-radiative recombination will give an IRE =1 even though the bandgap or ERE may change for different materials or optical environments. Each junction of our 4J solar cell, including the metamorphic junctions, has very respectable IRE quality. Indeed, the GaInP junction is very high since we have used a rear-heterojunction design and, while the GaAs junction could be improved at one-sun, it becomes nearly perfect at high currents.

SUBCELL JV CURVES

Using EL and LC analyses, we have collected considerable information about the performance characteristics of each subcell. We have also measured the JV curve of the 4J device when each junction is limiting. Assuming superposition and shifting the junction dark JV curves calculated from EL (which do not include series resistance) by the photocurrents calculated using the LC analysis, we subtract from the measured JV curves to determine the complete JV
curves of each junction including shunt resistance and reverse breakdown as shown in figure 6. Adding these subcell JV curves, again shifted by LC-calculated photocurrents, results in a very good simulation of the JV curve under arbitrary external illumination.

The external photocurrents, shown in table 1, calculated from EQE measurement indicate that the 4th junction would limit at one-sun AM1.5D conditions, but the LC analysis indicates that the 1st junction would limit. Measurements of the JV curve nominally at this condition are shown in figure 6 along with simulations from the reconstructed subcell JV curves. The disagreements in Jsc indicate the uncertainties involved in the measurement, but the shape of the JV curve of both measurements with the simulated one-sun curve are in good agreement. In contrast, a simulation of the JV curve if the QE-determined photocurrents are used shows a reverse breakdown characteristic. This illustrates the difficulty in determining the current-limiting junction of a well-matched 4J solar cell. The LC analysis may more accurately determine the current-limiting junction than the EQE, given measurement uncertainties. In addition, as the spectrum is varied in real-world conditions, we can expect to see reverse breakdown characteristics at some times during operation if any junction has a breakdown voltage less than the sum of the other junction Voc's. It is not yet clear what the implications of this will be in CPV system operations.

The predictive nature of reconstructing JV curves under arbitrary spectral conditions from a limited characterization set allows the cell designer to optimize the design of 4J solar cells to the energy yield in specific locations.

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**FLASH MEASUREMENTS**

We have illustrated in the previous section the sensitivity of the JV shape of a well current-matched 4J solar cell at one-sun to accurate illumination of each junction. This sensitivity extends to high-concentration measurements. While spectral adjustability of flash simulators has been less important for multijunction devices with only two current-matched junctions, this limitation has become a critical issue for current matched 3J and 4J devices. A spectrally-adjustable T-HIPSS flash simulator is currently coming online at NREL, but at the time of the completion of this paper, we have not yet been able to measure the performance of our 4J IMM with it. In figure 7, we show the concentrator results of a flash simulator with an uncontrolled spectrum that likely over-illuminates the 3rd and 4th junctions. These unofficial results indicate the limitations of the tunnel junctions and series resistance in our 4J IMM device and illustrate the overestimation of the FF by comparing with the official one-sun results. In this device, we see that the peak tunneling currents of the three tunnel junctions do not limit the device up to 1000 suns, but series resistance limits the maximum efficiency to about 400 suns. In addition, the predicted Voc from the EL measurements is shown to agree with the measured Voc up to at least 100 suns, while the electrical dark IV is only useful up to about 20 suns due to the effects of series resistance.
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REFERENCES