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Equivalent circuit models for triple-junction concentrator solar cells

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ABSTRACT

Characterizing the performance of terrestrial multi-junction solar cells under a broad range of sunlight concentration and operating temperatures is important for designing high concentration photovoltaic systems. Experimental data is available for these cells but a satisfactory cell model, calibrated over the full range of these operating conditions, was not yet presented. This study presents single-diode and two-diode equivalent circuit semi-empirical models for InGaP/InGaAs/Ge triple-junction cells, calibrated against available empirical data published by two cell manufacturers. The two-diode model offers a better fit to the experimental values compared to the single diode model. In particular, the two diodes model describes better the dependence of efficiency on concentration. However, some systematic deviations still exist in both models, mainly related to temperature dependence. Based on these results, two further modeling issues are identified as promising directions for further improvement of the models.

1. Introduction

Characterizing the performance of terrestrial multi-junction solar cells is critical for designing high concentration photovoltaic (HCPV) systems. These cells may operate over a range of incident radiation flux, typically a few hundred and up to 1000 suns, and a range of operating temperatures up to about 100 °C. The dependence of the cell's performance on these two operation parameters should then be well defined. Experimental data has been published for the widely used InGaP/InGaAs/Ge triple-junction cells: for cells made by Sharp the data is given for 25–120 °C, 1–200× [1–5], and for cells made by Spectrolab the data is for 25–120 °C, 1–1000× [6,7].

Semi-empirical cell models were suggested to relate the cell performance to known physical mechanisms, and to predict it as a function of temperature and concentration [6,8–13]. Two diodes equivalent circuit models were proposed in [8–10] but the combined effects of elevated temperature and high incident radiation flux were not studied. The model given in [8] was calibrated against InGaP/InGaAs/Ge cell data only at room temperature and 1 sun. The model presented in [9] was calibrated against measurements at room temperature and for the concentration range of 1–1000×. The temperature sensitivity predictions of the model given in [9,10] were successfully compared to the Sharp cell data at 1 sun and temperatures below 120 °C [10]. The coefficients were optimized to fit the *I–V* curves measured data. In all cases, the resulting semi-empirical coefficients were not reported.

A single diode equivalent circuit model, calibrated for both high concentration and temperature levels, was presented in [11,12]. The model included a separate *I–V* relationship for each subcell. The model predictions were calibrated against the Sharp cell data [1–5] optimizing the coefficients to fit the measured efficiency as *I–V* data was not available. The results indicated that at high concentrations, the open circuit voltage and efficiency-temperature coefficients predictions, which are critical, deviate from the data. A single diode model, calibrated against the Spectrolab C1MJ cell data at elevated temperature and intensity, was later proposed in [6] where a lumped cell *I–V* relationship was considered with a single ideality factor. The resulting coefficients far exceeded the expected range. A qualitative comparison between the predicted and measured open circuit temperature coefficients at different concentration levels was presented but a comparison between the predicted and measured efficiency temperature coefficients was not given. A single diode model was also suggested by [13]. The model was calibrated against triple-junction cell data at temperatures below 120 °C and concentration level up to 700×. To extract the model coefficients, a fitting procedure with respect to the RMS errors in the *I–V* predictions was carried out. The resulting coefficients' values were not reported. The resulting RMS errors were below 2% but a comparison between the predicted cell temperature coefficients (efficiency and voltage) and the measured values was not provided. Because the predicted temperature coefficients at high

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concentration levels were not presented, the inaccuracy of the single diode model at these conditions, as was unveiled earlier [11,12] could not be examined.

More sophisticated, distributed (network) cell models were recently proposed. In this approach, the cell is divided into many small elementary cells (hundreds or thousands) to increase accuracy. The downside of the approach is that it is complex to implement and requires high computational resources, making it unsuitable at the engineering level. A distributed model for single junction GaAs cell was presented in [14] and validated against empirical data at room temperature and concentration levels of 1, 50 and 560 suns. A distributed model for a triple junction InGaP/InGaAs/Ge cell was suggested in [15] and validated against empirical data at room temperature for concentration levels of up to 5 suns. The results have shown that under the AM1.5 spectrum and uniform illumination, the predictions of the distributed model are similar to those of the much simpler lumped (non-distributed) models, and therefore the added complexity of the distributed models is hard to justify. A clear advantage of the distributed models is reported only in the case of non-uniform illumination over the cell. In the present work only the case of uniform illumination will be addressed.

A robust cell model that will be valid and accurate over a broad range of temperatures and flux concentration should take into account the variations in material properties over the intended range of operation. Models presented in the literature describe the strong temperature dependence of diode behavior, but in many cases assume that the bandgap for each junction is constant (e.g., [10,13]). While the temperature variation in material bandgap is small relative to the diode current variations, nevertheless it may be significant when requiring high correspondence of the model to experimental data. Another aspect usually ignored in published models is the difference in the junction alloy composition between cells provided by different manufacturers, which also affects the junction bandgap. This aspect should be addressed in a generalized model as well that is not restricted to a particular cell.

Thus, a satisfactory performance model for triple-junction cells, well predicting the cell performance and temperature characteristics over a broad range of operating conditions and for different cells, is not yet available. In the current study, single and two diodes equivalent circuit models for triple-junction cells are analyzed in detail focusing on the temperature and concentration effects. The models were calibrated against published experimental data with the help of regression analysis. Based on the current results, two modeling issues related to variations of material properties are indicated as a promising direction for further improvement of the cell performance model.

2. Equivalent circuit models

2.1. Single diode model

A two-terminal equivalent circuit model for a triple-junction cell with a single-diode for each junction is presented in Fig. 1. The subcells I–V relationship is given by

$$J_L = J_{sc,i} - J_{o,i}\left(e^{\frac{q(V_i + J_L AR_{s,i})}{n_i k_B T}} - 1\right) - \frac{V + J_L AR_{s,i}}{AR_{sh,i}} \quad (1)$$

where i represents the subcell number (1=top, 2=medium and 3=bottom). J_{sc}, J_o and J_L are the short circuit, the diode reverse saturation and the load current densities (currents per unit cell area), respectively. q is the electric charge, V is the voltage, n is the diode ideality factor (typically between 1 and 2), k_B is Boltzmann's constant, T is the absolute temperature and A is the cell area.

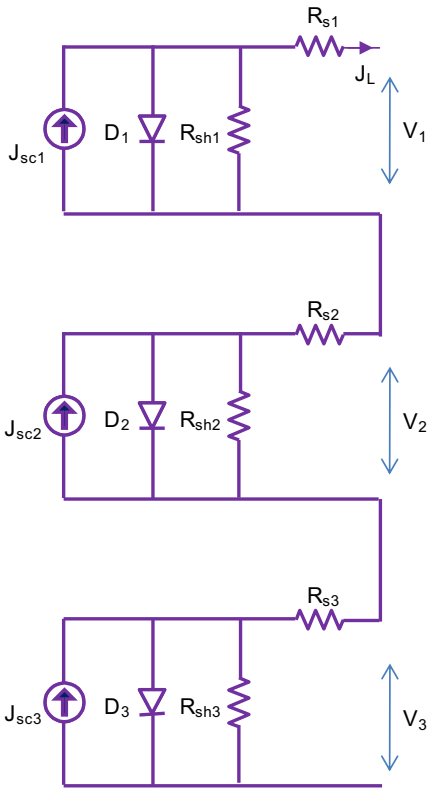

Fig. 1. One-diode equivalent circuit cell model.

R_s and R_{sh} are the series and the shunt resistances, respectively. It is assumed that the cell temperature is uniform.

The reverse saturation current is strongly temperature dependent and is given by [16]

$$J_{o,i} = \kappa_i T^{(3+\gamma_i/2)} e^{(-E_g/n_i k_B T)} \quad (2)$$

where E_g is the energy band gap and κ and γ are constants where γ is typically between 0 and 2. Because in Eq. (1) the reverse saturation current is modeled by a single term, it represents recombination in both the depletion and the quasi-neutral regions.

The energy band gap is a weakly decreasing function of temperature; hence the short circuit current increases with temperature. This variation is sometimes neglected in published cell models where the bandgap is taken as a constant [13]. However, when high accuracy of the model predictions over a broad range of temperatures is desired, this second-order effect may be significant. The bandgap is given as a function of temperature by [17,18]

$$E_g = E_g(0) - \frac{\alpha T^2}{T + \sigma} \quad (3)$$

where α and σ are material dependent constants.

When junctions in a cell are made from alloys rather than pure materials, and the alloy composition chosen by each manufacturer is somewhat different, differences in bandgap may occur even if the materials are nominally similar. Including the impact of material composition in a cell model allows additional flexibility to represent different cells within the same model. The band gap for semiconductors' alloys can be determined by the following linear superposition [19]:

$$E_g(A_{1-x}B_x) = (1-x)E_g(A) + xE_g(B) - x(1-x)P \quad (4)$$

$A_{1-x}B_x$ is the alloy composition and P [eV] is an alloy dependent parameter that accounts for deviations from the linear approximation. The short circuit current, J_{sc}, depends on the energy band