The Single Diode Model and Ultra-High Efficiency HJT Cells

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Introduction

Module technology is undergoing rapid evolution, with the currently dominant PERC technology expected to be replaced by n-TOPCon and heterojunction (HJT) devices with stabilized cell efficiencies exceeding 26% in the next decade[1]. The actual timeframe to reach this mark may be considerably shorter, in the past year Longi has reported a HJT device with a record cell efficiency of 26.81%[2], while SunDrive Solar from Australia have demonstrated a cell efficiency of 26.41%[3] for a HJT cell with copper plated contacts.

A key feature of HJT is extremely low carrier recombination, both in the silicon bulk and at the surfaces/contacts. This means that intrinsic recombination, consisting of Auger and radiative components[4], becomes significant. This alters the I-V characteristics of the device, resulting in a significant boost to fill factor[5].

This presents a challenge for simulation of these devices in the field. Current yield simulation software, such as PVSyst, SAM and pvlib, almost exclusively uses the single-diode model to describe module behaviour. This model is relatively straightforward and has, to date, provided sufficient accuracy for these simulations. However, it is not clear how well this model describes devices approaching the intrinsic recombination limit.

This paper investigates how well the single-diode describes these devices, in comparison with more complex approaches.

Methodology

Two datasets were used in this study. The first is data measured at SunDrive solar, and the second was simulated data from Quokka3 [6], [7]. The measured data is for heterojunction cell with an STC conversion efficiency of 24.5%, in which intrinsic recombination can be reasonably neglected. In contrast, Quokka simulations were performed using a model of the current world record cell, with a 26.81% conversion efficiency under STC conditions. This paper present fits to data under 1,000 W/m^2 illumination at temperatures between 15-50^{o}C.

Data fitting was performed using the '2/3-Diode Fit' package[8]. Two approaches were used. The first method attempted to mimic the description of the cells within PVSyst ('PVSyst fit')[9]. The results at STC (25^{o}C, 1000 W/m^2) were fitted using the single-diode equation:

$$I = I_{ph.ref} - I_{0.ref}\left(e^{\frac{q(V+IR_S)}{\gamma k T_{C.ref}}} - 1\right) - \frac{V+IR_S}{R_{SH}} \qquad (1)$$

Once reference values were obtained through the STC fit the behaviour at different temperatures was calculated using:

$$I_{ph} = \left(\frac{G}{G_{ref}}\right)\left[I_{ph.ref} + \mu_{Isc}\left(T_c - T_{c.ref}\right)\right] \qquad (2)$$

$$I_0 = I_{0.ref}\left(\frac{T_c}{T_{c.ref}}\right)^3 e^{\left[\left(\frac{qE_g}{\gamma k}\right)\left(\frac{1}{T_{c.ref}} - \frac{1}{T_c}\right)\right]} \qquad (3)$$

Where T_C is the cell temperature and $T_{c.ref}$ is 298.15K. Fits were performed both with a fixed γ and with a linear dependence of γ on T. In a slight departure from the method used by PVSyst this linear dependence was evaluated through best fits to the data (rather than simply the MPP) at 25 and 45°C.

μ_{Isc} is the only parameter that is not determined from the STC fit, and was instead obtained through a linear fit to the short circuit currents across the temperature range.

For the 3-diode model the results at each temperature were fitted the method of Suckow et al.[8]. In order to reduce the number of free parameters and maintain physical meaning the ideality factors were fixed at n=0.67, 1 for the first two diodes, and n=2 for resistance limited recombination. The first diode was thus intended to account for intrinsic recombination, while the second was for 'traditional' sources of recombination. This left 7 free parameters: $I_{ph}, I_{0.1}, I_{0.2}, I_{0.3}, R_S, R_{SH}$, and R_{rec}.

While this approach yielded near-perfect fits, it does not constitute a useful model for predicting cell output in the field, under a wide range of conditions. Therefore, a further fitting step was performed to determine temperature coefficients for each of these parameters. It was found that R_S, R_{SH} and R_{rec} were essentially temperature independent. I_{ph} was also well described with a linear temperature dependence as per Equation 2.

The diode saturation currents might be expected to follow a similar temperature dependence to Equation 3. The coefficients were slightly simplified and $I_{0.2}, I_{0.3}$ were fitted using:

$$I_{0.x} = \alpha T^3 e^{\frac{-\beta}{T}} \quad (4)$$

While the diode intended to describe intrinsic recombination was fitted according to:

$$I_{0.1} = \alpha e^{\frac{-\beta}{T}} \quad (5)$$

where α and β are fitting parameters. The data and fits obtained are presented in Figure 1.

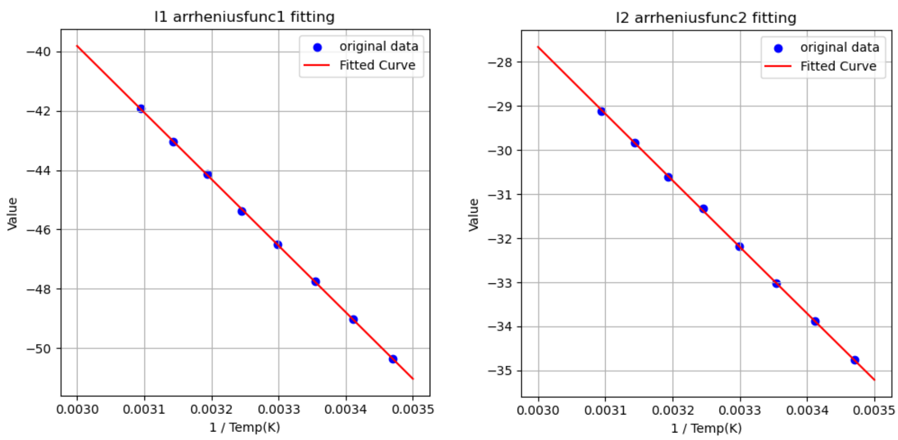

Figure 1: Arrhenius plots of A) I_{01} and B) I_{02} along with the obtained fits

Results and Discussion

Fig 2 presents the results of the PVSyst fit to the 24.5% efficient cell measured at SunDrive, with a constant γ. It can be seen that this provides an acceptable fit, particularly in the vicinity of the maximum power point. Despite the slight overestimation of open-circuit voltage at higher temperatures there appears to be limited value in using a more complex model to describe this cell.

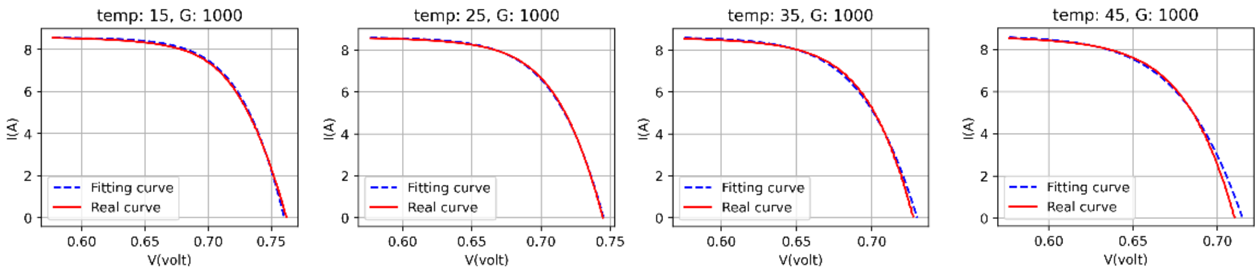

Figure 2: PVSyst fits to cells measured at SunDrive for temperatures between 15-50ºC

In contrast, when the same fitting procedure was applied to the Quokka simulation the model diverged significantly from the results, as seen in Figure 3. Using a fixed γ the model underpredicts performance at temperatures below 25ºC, and overpredicts when temperatures are above 25ºC. The introduction of a linear dependence of γ on temperature (-0.052%/ºC, well outside the recommended range in PVSyst) significantly improved the results, however the behaviour nearing open circuit was still poorly described.

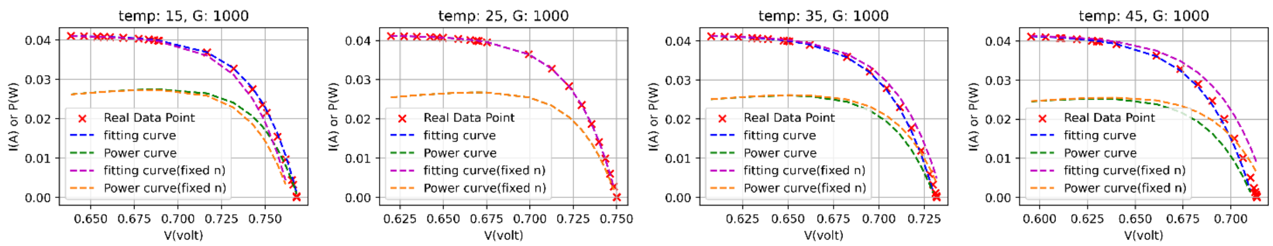

Figure 3: PVSyst fits to Quokka data at temperatures between 15-50ºC

The 3-diode model is able to predict the simulated results much more accurately, as seen in Figure 4.

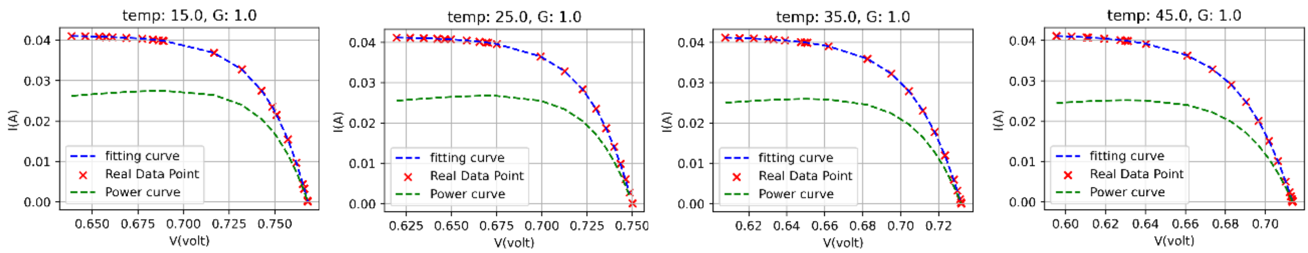

Figure 4: 3-diode fits to Quokka data at temperatures between 15-50ºC

The results for both models, and resulting errors in predicted maximum power are summarized in Table 1. The 3-diode fit demonstrates significant reductions in both the RMSE and the error at maximum power point, particularly at elevated temperatures. This improvement is expected to be even greater once variations in illumination are considered.

Table 1 Cell parameters per cm2 from Quokka simulation and fits.

Temp (ºC)	Quokka Results				PVSyst Fit (varying γ)		3-Diode Fit	
	V_{OC} (mV)	J_{MP} (mA)	V_{MP} (mV)	P_{MPP} (mW)	RMSE (mA)	P_{MPP} Error (%)	RMSE (mA)	P_{MPP} Error (%)
15	768	39.9	689	27.46	0.59	0.09%	0.028	0.07%
20	759	39.9	680	27.09	0.29	0.10%	0.022	0.05%
25	750	39.9	670	26.71	0.055	0.14%	0.05	0.04%

30	741	39.9	660	26.33	0.32	0.16%	0.043	0.04%
35	732	39.9	651	25.95	0.60	0.17%	0.047	0.01%
40	723	39.9	641	25.56	0.94	0.20%	0.051	0.04%
45	714	39.9	631	25.17	1.16	0.22%	0.065	0.03%
50	704	39.9	621	24.78	1.55	0.22%	0.135	0.05%

One point of interest is that within Quokka, intrinsic recombination is assumed to follow the equations of Niewelt et al.[4]. These equations do not have any explicit dependence on temperature, and the carrier densities under illumination should also have minimal temperature dependence. However, the saturation current density associated with intrinsic recombination in the 3-diode model used in this paper increases exponentially with temperature. Further work will be required to resolve this contradiction and develop an alternative description of intrinsic recombination if required.

Conclusion and Future Work

Simply applying current models of PV modules will lead to inaccuracies when simulating devices that approach the intrinsic recombination limit. This can be resolved using more complex models, however, the potential trade-offs between accuracy and performance will be the subject of future investigations. In the ideal case a generic description of intrinsic recombination might be developed, which would further reduce the number of fitting parameters.

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