ORIGINAL RESEARCH ARTICLE

Practical Verification and Comparative Analysis of One- and Two-Diode Models of Space Triple-Junction InGaP$_2$/InGaAs/Ge Solar Cell

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Abstract

The practical verification and comparative analysis of one- and two-diode models of a 31.6% efficiency space triple-junction InGaP$_2$/InGaAs/Ge solar cell is presented. Based on the experimental I–V curves of the sub-cells under the air mass 0 (AM0) spectral condition, the diode characteristics of the sub-cells are extracted by the mathematical model of the solar cell diode equivalent circuits. The circuit simulation software, LTSpice, is used to establish the equivalent one-diode and two-diode circuit models of the triple-junction solar cell. The simulation results are compared with the experimental observations of the triple-junction solar cell I–V characteristics under the AM0 spectral condition, demonstrating that the difference in value between the one-diode model and the practical verification cell-in-cell efficiency is 4%, while that of the two-diode model is 0.4%, which may indicate that the two-diode model has better accuracy in the circuit simulation of triple-junction InGaP$_2$/InGaAs/Ge solar cells. This work will be helpful in the structural optimization design of space solar cells and the circuit simulation of spacecraft solar arrays.

Graphical Abstract
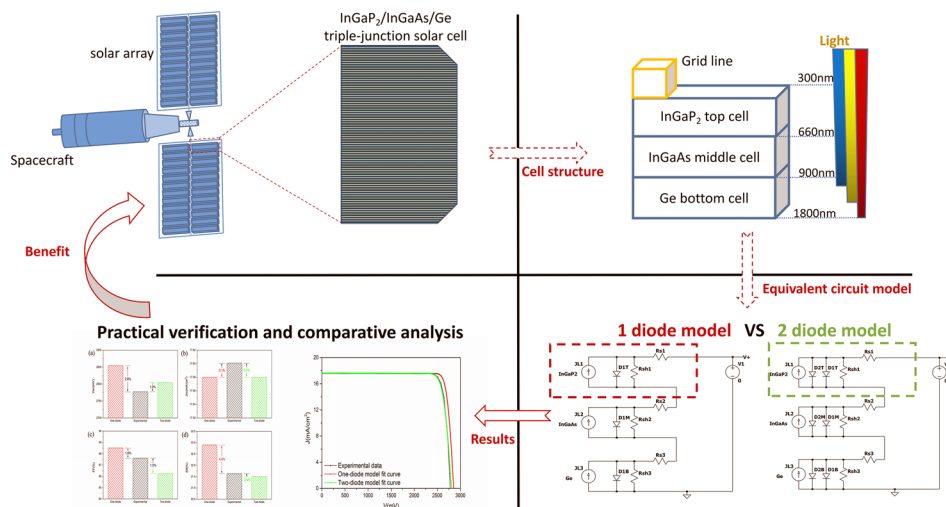
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Introduction

As the sole source of power for most spacecraft, solar cells are critical to mission success. Benefiting from a wide band gap and high-temperature tolerance, triple-junction InGaP$_2$/

InGaAs/Ge solar cells are widely used in spacecraft solar cell arrays.[1,2] Due to the high material cost and complex production processes of triple-junction InGaP$_2$/InGaAs/Ge solar cells, accurate modeling of the cells is required to simulate their nonlinear output characteristic curves[3] to improve the utilization of solar energy, thereby reducing the power generation costs. The key factors affecting the accuracy and validity of the simulation model are the physics–mathematical model and modeling parameters. Since a triple-junction solar cell is composed of three sub-cells and has multiple parameters to be calibrated, simulating a non-ideal triple-junction cell is highly challenging. As classical physics–mathematical theory models, the one-diode model and the two-diode model are widely used in the simulation of solar cells. Bibi et al. simulated the circuit of a perfect triple-junction InGaP$_2$/InGaAs/Ge solar cell and compared the output performance with single-junction and double-junction solar cells,[4] while Wang et al. predicted the performance of multi-junction solar cells by using different simulation model parameters.[5] However, less attention has been paid to the practical validation of one-diode and two-diode models for triple-junction InGaP$_2$/InGaAs/Ge solar cells, only Segev et al. has compared two simulation models for triple-junction concentrator cells, concluding that both models yielded less than 2.5% total RMS error.[6]

Therefore, based on the measured I–V curve, this paper determines the one-diode and two-diode model characteristic parameters of triple-junction InGaP$_2$/InGaAs/Ge sub-cells and establishes the physics–mathematical model of the triple-junction InGaP$_2$/InGaAs/Ge solar cell by applying the basic units of the one-diode model and the two-diode model. The accuracies of the one-diode model and two-diode model of the triple-junction InGaP$_2$/InGaAs/Ge solar cell have been analyzed by comparing them with the measured performance of the triple-junction cell.

Equivalent Diode Model of Solar Cell

For many types of solar cells commonly used in commercial energy operation enterprises, two common models are the one-diode and the two-diode.[7] Both models can be used to simulate the I–V output characteristic curves of solar cells and calculate their photoelectric conversion efficiency.[8] The one-diode model uses a single diode to simulate the P–N junction of the solar cell, and a parallel current source to simulate the photogenerated current.[9] In contrast, the two-diode model simulates a solar cell using two parallel diodes,
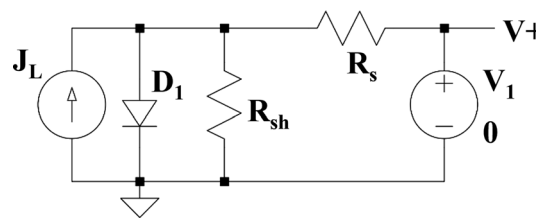

Fig. 1 The equivalent circuit model of a one-diode single-junction solar cell.
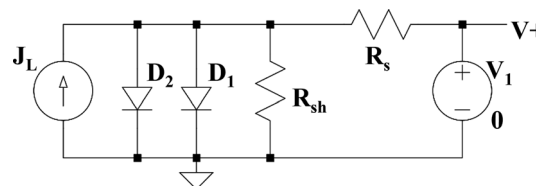

Fig. 2 The equivalent circuit model of a two-diode single-junction solar cell.

where the second diode is used to assume the recombination phenomena in the junction.[10,11] In a non-ideal solar cell, its current has a certain loss from the ideal state, which is replaced by a series of resistance in the equivalent model.[12,13] In addition, a shunt resistor is used to provide a shunt path for the photogenerated current, which causes the current generated by the solar cell to drop and lead to power loss.[14,15]

One-Diode Model Equivalent Circuit

The solar cell equivalent circuit of the one-diode model is depicted in Fig. 1, and the corresponding mathematical model can be expressed by Eq. 1 [16]:

$$J = J_L - J_{01}\left\{ exp\left[\frac{q(V + JR_s)}{n_{01}kT} \right] - 1 \right\} - \frac{V + JR_s}{R_{sh}} \qquad (1)$$

where J represents the current density, J_L denotes the light, J_{01} the saturation current in the diode D_1, V is the voltage, n_{01} the diode D_1 ideal factor, kT/q is the thermal voltage, R_s the series resistance, and R_{sh} denotes the shunt resistance.

Two-Diode Model Equivalent Circuit

The solar cell equivalent circuit of the two-diode model is shown in Fig. 2, and the corresponding mathematical model can be expressed by Eq. 2 [17]:

$$J = J_L - J_{01} \left\{ \exp\left[\frac{q(V+JR_s)}{n_{01}kT}\right] - 1 \right\}$$
$$- J_{02} \left\{ \exp\left[\frac{q(V+JR_s)}{n_{02}kT}\right] - 1 \right\} - \frac{V+JR_s}{R_{sh}} \quad (2)$$

where J represents the current density, J_L denotes the light, J_{01} the saturation current in the diode D_1, J_{02} the saturation current in the diode D_2, V is the voltage, n_{01} the diode D_1 ideal factor, n_{02} the diode D_2 ideal factor, kT/q is the thermal voltage, R_s the series resistance, and R_{sh} denotes the shunt resistance.

Results and Discussions

One-Diode Model Parameters Extraction

The triple-junction solar cell and the sub-cells were measured under air mass 0 (AM0) light conditions and 25 °C ambient temperature. To extract the parameters of the sub-cells, the parameters of the equivalent diode model were extracted using a fitting simulation program based on MAT-LAB.[18–20] By fitting the experimental I–V data of every single sub-cell of the triple-junction InGaP$_2$/InGaAs/Ge solar cell and setting the illumination intensity and environment temperature corresponding to the measurement conditions, each sub-cell equivalent diode model parameters were extracted according to the curve characteristics. As shown in Fig. 3, the fit curve of the one-diode model for the bottom cell aligns well with the experimental observations. The root mean square error (RMSE) of the bottom cell is 0.134 mA/cm^2, while the diode characteristic parameters extracted are the diode D_1 ideal factor (n_1) = 1.07, and the

saturation current in the diode $D_1 (J_{01}) = 6.97 \times 10^{-7}$ A/cm^2. It can be observed that the fitting of the middle cell also has high accuracy, and the RMSE is 0.052 mA/cm^2. The middle cell diode model parameters obtained from the curve are $n_1 = 0.97$, $J_{01} = 1.49 \times 10^{-20}$ A/cm^2. For the top cell, the RMSE is 0.028 mA/cm^2, from which we can see that the gap between the fit curve and the observed data is insignificant, which indicates that the model is accurate and effective. The parameters of the one-diode model top cell obtained from the fit curve are $n_1 = 1.10$, $J_{01} = 1.83 \times 10^{-25}$ A/cm^2.

Two-Diode Model Parameters Extraction

Figure 4 shows the curve fitting and parameter extraction results of the two-diode model of the same sub-cells. It can be seen that there is also no obvious deviation between the fit curve and the experimental observations. By calculating the error between the fit curve and the experimental observations of the bottom cell, the RMSE of the one-diode model and the two-diode model are both shown to be 0.134 mA/cm^2, which demonstrates the accuracy and validity of the two models. Calculated from the I–V curve, the parameters of the two-diode model can be determined as $n_1 = 1.00$, the diode D_2 ideal factor (n_2) = 1.36, $J_{01} = 5.79 \times 10^{-15}$ A/cm^2, and the saturation current in the diode $D_2 (J_{02}) = 2.46 \times 10^{-5}$ A/cm^2. For the middle cell parameters extraction, the RMSE of the two-diode model is about 0.058 mA/cm^2, which is slightly higher than that of the one-diode model by 0.006 mA/cm^2, but does not affect the validity of the two-diode model. The parameters of the middle cell in the two-diode model are $n_1 = 1.00$, $n_2 = 2.26$, $J_{01} = 4.01 \times 10^{-20}$ A/cm^2, and $J_{02} = 1.80 \times 10^{-10}$ A/cm^2. As can be observed, the parameters of the top cell in the two-diode model are found to be $n_1 = 1.00$, $n_2 = 1.68$, $J_{01} = 7.50 \times 10^{-28}$ A/cm^2,
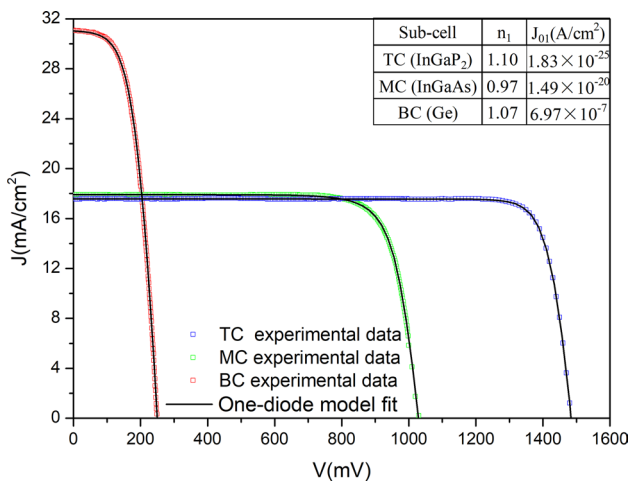

Sub-cell	n_1	J_{01}(A/cm^2)
TC (InGaP$_2$)	1.10	1.83×10^{-25}
MC (InGaAs)	0.97	1.49×10^{-20}
BC (Ge)	1.07	6.97×10^{-7}

Fig. 3 The one-diode model fit curve and parameters extraction of the bottom cell (*BC*), the middle cell (*MC*), and the top cell (*TC*).

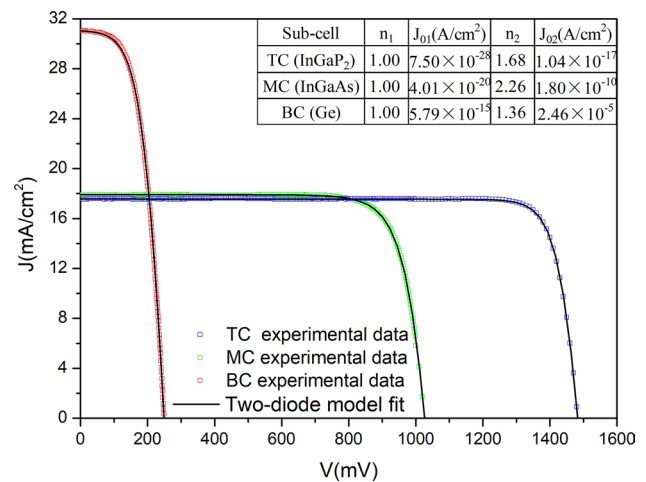| Sub-cell	n_1	J_{01}(A/cm^2)	n_2	J_{02}(A/cm^2)
TC (InGaP$_2$)	1.00	7.50×10^{-28}	1.68	1.04×10^{-17}
MC (InGaAs)	1.00	4.01×10^{-20}	2.26	1.80×10^{-10}
BC (Ge)	1.00	5.79×10^{-15}	1.36	2.46×10^{-5}

Fig. 4 The two-diode model fit curve and parameters extraction of the bottom cell (*BC*), the middle cell (*MC*), and the top cell (*TC*).

Table I One-diode and two-diode models extracted parameters summary

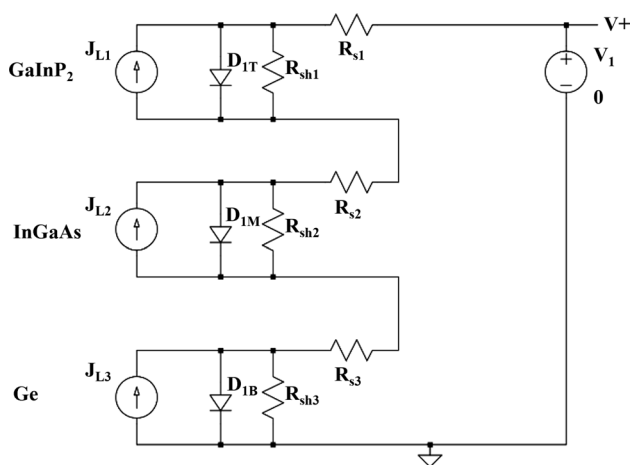| Sub-cells	One-diode model parameters	Two-diode model parameters
Bottom cell (Ge)		
n_1	1.07	1.00
J_{01} (A/cm^2)	6.97×10^{-7}	5.79×10^{-15}
n_2	–	1.36
J_{02} (A/cm^2)	–	2.46×10^{-5}
Middle cell (InGaAs)		
n_1	0.97	1.00
J_{01} (A/cm^2)	1.49×10^{-20}	2.26
n_2	–	4.01×10^{-20}
J_{02} (A/cm^2)	–	1.80×10^{-10}
Top cell (InGaP$_2$)		
n_1	1.10	1.00
J_{01} (A/cm^2)	1.83×10^{-25}	1.68
n_2	–	7.50×10^{-28}
J_{02}(A/cm^2)	–	1.04×10^{-17}

Fig. 5 The equivalent circuit model of a one-diode triple-junction solar cell, when D_{1T} denotes the top cell diode, D_{1M} denotes the middle cell diode, and D_{1B} denotes the bottom cell diode.

Fig. 6 The equivalent circuit model of a two-diode triple-junction solar cell, when D_{1T} and D_{2T} denote the top cell diodes, D_{1M} and D_{2M} denotes the middle cell diodes, D_{1B} and D_{2B} denote the bottom cell diodes.

Fig. 7 The one-diode and two-diode models simulating the I–V curve compared to the experimental data.

and $J_{02} = 1.04 \times 10^{-17}$ A/cm^2. From the RMSE calculation, it can be seen that the RMSE of the fitted and experimental observations of the two-diode model top cell is 0.035 mA/cm^2, which is about 0.007 mA/cm^2 higher than that of the one-diode model. Even though the value of the RMSE of the two-diode model has slightly increased, from a macroscopic analysis, the calculated errors of the two models are relatively low, indicating that there is no obvious dispersion between the fit curve and the experimental observations in the two models; no obvious outliers were observed.
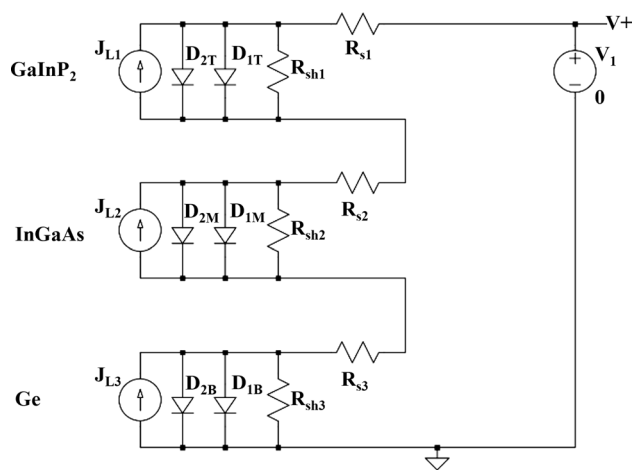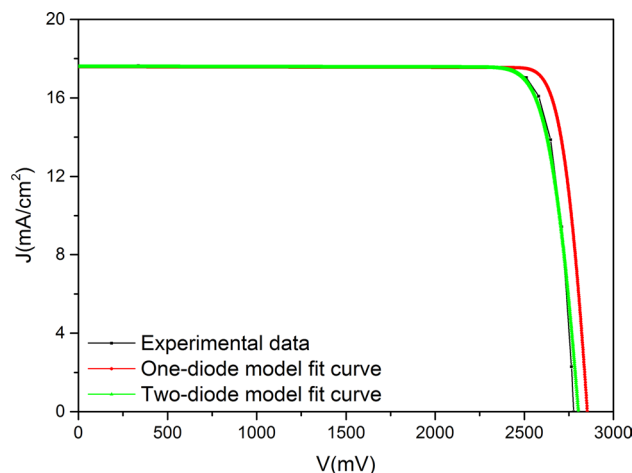
Comparative Analysis of Triple-Junction Solar Cell Performance Between the One-Diode and Two-Diode Models

The parameters extracted by the two models are summarized in Table I.

As shown in Figs. 5 and 6, the triple-junction InGaP$_2$/InGaAs/Ge solar cell with one diode or two diodes as the basic unit has been modeled by LTSpice software,[4,21–24] and the corresponding parameters are set. The extraction of the model parameters is defined in the content discussed above. The modeling uses each sub-cell parameter to simulate the physical characteristics of each P–N junction of the triple-junction solar cell, and performs simulations to obtain the

output performance of the triple-junction solar cell. Meanwhile, the standard triple-junction solar cell for space-use mass production was tested for the illumination I–V curve. The settings of the illumination and the ambient temperature are the same as the simulation input parameters, so that the consistency of other conditions is maintained. By comparing the experimental observations and the simulation results of the two models, their effectiveness in modeling triple-junction solar cells can be compared and analyzed. This chapter discusses the accuracy results for both models.

From the I–V curves of the solar cell shown in Fig. 7, there is no significant difference in the short-circuit current between the one-diode model, the two-diode model, and the experimental cell, but the open-circuit voltage of the triple-junction solar cell of the one-diode model is significantly higher than the experimental observations. At the same time, only a slight increase in the open-circuit voltage of the two-diode model is observed. Compared with the experimental cell, the maximum power point of the one-diode model has a discernible shift to the right, while the two-diode model is slightly shifted to the left. The performance curve of the two-diode model shows a small difference from the experimental

cell, which indicates that the coincidence between the two is good, while the device performance simulated by the one-diode model is significantly better than the experimental cell and the two-diode model simulation result.

In the application of solar cells, open-circuit voltage (V_{OC}), short-circuit current (J_{SC}), fill factor (*FF*), and power conversion efficiency (E_{ff}) are the most important electrical parameters. Figure 8 shows comparative analysis results of the triple-junction solar cell performance, including V_{OC}, J_{SC}, *FF,* and E_{ff}. In the results of the open-circuit voltage, the one-diode model simulation result is 2.8% higher than the experimental cell, while the two-diode model shows only a 1% difference. Moreover, the performance of the two models on the short-circuit current indicates that the difference between the two models and the experimental observations is not obvious, both being marginally lower than the experimental cell by 0.1%, which may be due to errors in the measurement process. Furthermore, the FF calculated from the one-diode model is increased by about 1.0% compared to the experimental observations, while the calculated result of the two-diode model is reduced by about 1.5%. The difference is small, but it can be seen that the direction of the difference
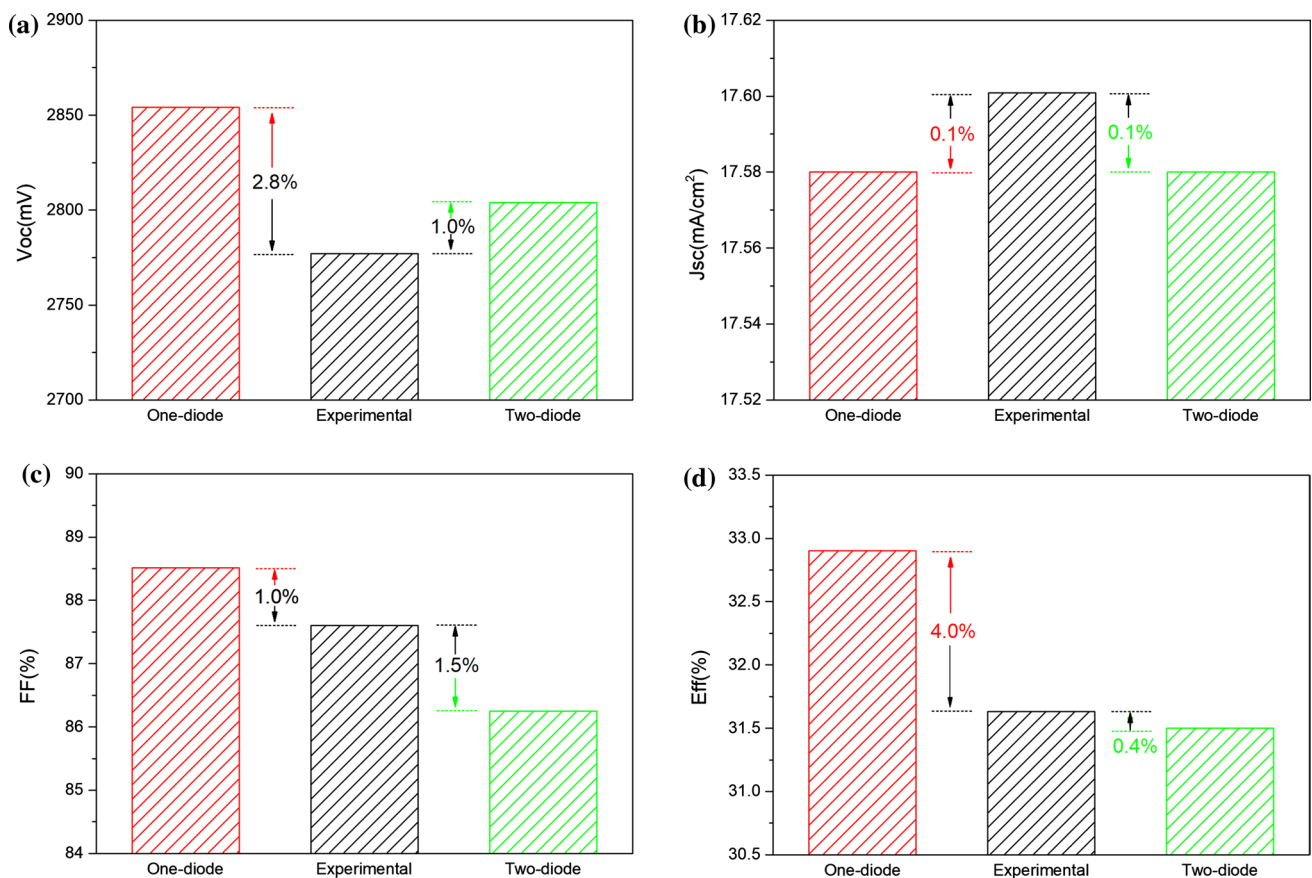

Fig. 8 The one- and two-diode cell model simulated performance characteristics compared to the experimental cell: (a) V_{OC}, (b) J_{SC}, (c) *FF,* and (d) E_{ff}.

between the two models is the opposite. This illustrates that the device performance simulated by the one-diode model is superior to that of the actual device, while, on the contrary, when the two-diode model is used for calculations, the device performance is slightly lower than the actual device. This conclusion is more obvious in the comparative result of solar cell efficiency, which shows a relatively larger difference in the calculation results between the two models. The cell efficiency of the one-diode model is about 4.0% higher than that of the standard cell, while the cell efficiency of the two-diode model is lower than the experimental cell by roughly 0.4%.

The results show that for, triple-junction InGaP$_2$/InGaAs/Ge solar cells, the two-diode model is more accurate than the one-diode model, and can more effectively simulate the output performance and characteristics of produced solar cells. Even if the measured and simulated light intensity conditions are both in the AM0 spectrum, that is, the power density is about 1353 W/m^2, there are still larger deviations shown in the one-diode model. This is probably because multi-junction solar cells have multiple P–N junctions of different materials, so even under high illumination and high voltage conditions, the recombination in the junctions is still influential, thus affecting the accuracy and validity of the model. Single-junction GaAs solar cells or silicon solar cells have a lower impact on the second diode under high illumination conditions,[25–27] but for triple-junction solar cells, characterizing the output performance and device physics under any illumination conditions should be simulated using a two-diode model to obtain more accurate results.

Conclusions

We have used LTSpice for circuit simulation to establish the one-diode and two-diode models of a standard triple-junction InGaP$_2$/InGaAs/Ge solar cell for space use, and have conducted a comparative analysis of the different models' simulation accuracy in cell output performance. Firstly, diode mathematical models were fitted and the diode parameters were extracted from the fit curve. The fitting accuracy of the two models is illustrated by the RMSE. By calculating the fitting accuracy, both models are valid, and there is no obvious deviation value, so the extracted parameters are meaningful. Then, based on the diode characteristic parameters, the one- and two-diode models of the triple-junction solar cell are established separately by applying LTspice software. By comparing the simulation results of the one- and two-diode models with the experimental I–V curves, the two-diode model shows more accurate results. There is a 4.0% difference between the simulation results of the one-diode model and the experimental results in the solar cell efficiency, while there is only a 0.4% difference between

the two-diode model simulated results and the experimental results. This is probably because the recombination of the triple-junction solar cells has a non-negligible influence. The present work will be helpful in the structural optimization design of space solar cells and the circuit simulation of spacecraft solar arrays.

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