

Article

Recombination Parameters of the Diffusion Region and Depletion Region for Crystalline Silicon Solar Cells under Different Injection Levels

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Abstract: In order to maximize performance in all conditions of use, and to model exactly the performance of solar cells, it is very important to study the recombination parameters under different injection levels. In this paper, the recombination parameters and their effect on the output performance of solar cells are investigated under different injection levels for the full-area aluminum back surface field (Al-BSF) solar cell and passivated emitter and rear cell (PERC) solar cell for the first time. It is found that the recombination parameter J_{01} of the diffusion region and the recombination parameter J_{02} of the depletion region for the PERC solar cell are smaller than those of the Al-BSF solar cell under the same injection level. A new finding is that the recombination parameter J_{01} of Al-BSF solar cells increases quickly with the decreasing injection level compared with PERC solar cells. Finally, the J_{01}/J_{02} of Al-BSF and PERC solar cells is investigated, and the effects of J_{01}/J_{02} on the electrical parameters are also analyzed for Al-BSF and PERC solar cells under different injection levels. The obtained conclusions not only clarify the relationship between the recombination parameters and injection levels, but also help to improve cell processes and accurately model daily energy production.

Keywords: recombination parameter; silicon; solar cells; solar cells; injection level

1. Introduction

The conversion efficiency of crystalline silicon solar cells strongly depends on the carrier recombination behavior [1–3]. The recombination properties of the diffusion region and depletion region are related to light injection levels, i.e., cumulative integrated irradiance. Characterizing the recombination for solar cells under different injection levels is very important to maximize the outdoor performance of solar cells and accurately model daily energy production under non-standard test conditions [4–6]. However, clarifying the recombination parameters in different regions of a solar cell is very complicated, particularly for solar cells with different technologies and under different injection levels [7–9]. Chih-Tang Sah et al. made a contribution to the theory of carrier generation–recombination in the space-charge region of a p–n junction, where the recombination behavior can be expressed by the reverse saturation current density [10]. Kane and Swanson estimated the emitter saturation current density by measuring the effective lifetime [11]. Fa-Jun Ma et al. gave an advanced model of the effective minority carrier lifetime for passivated crystalline silicon wafers [12]. Andres Cuevas et al. studied carrier transportation and surface passivation in solar cells [13]. Robert Dumbrell et al. made a contribution on metal contact recombination [14]. Achim Kimmerle et al. studied the origin of the apparently reduced recombination parameter of highly doped regions [15–17]. Other authors have used the measured current–voltage (I–V) characteristics of solar cells in conjunction with computer simulations to obtain the recombination

parameters in solar cells under equilibrium conditions [18–22]. However, recently, Andres Cuevas indicated that the reverse saturation current density of a solar cell under illumination differs from that in equilibrium. He thought that the reverse saturation current density should be called the recombination parameter when a solar cell is illuminated [23]. Although some researchers ever investigated the recombination parameters of solar modules using a double-diode model, the estimated parameter of a solar module could not reflect the recombination behavior of a solar cell accurately, owing to soldering and encapsulation [24–29]. People often understand the recombination behavior of solar cells by measuring minority carrier lifetime and modeling, but it is generally not possible to detangle recombination in the different regions for solar cells [30]. To date, almost no one has studied the recombination parameter J_{01} of the diffusion region and the recombination parameter J_{02} of the depletion region for full-area aluminum back surface field (Al-BSF) and passivated emitter and rear cell (PERC) silicon solar cells under different injection levels [31–33]. Few studies have been conducted on the recombination parameters and their effect on the output performance of solar cells that change with the injection level.

At present, the PERC silicon solar cell and the Al-BSF silicon solar cell are the two main structures in the photovoltaic industry. Although Al-BSF silicon solar cells and PERC solar cells feature a homogeneous emitter on the front side, the structure of PERC solar cells is slightly different from that of Al-BSF solar cells. The recombination behavior of PERC solar cells is different from that of Al-BSF solar cells when the two types of solar cells are biased in the forward direction [34–37]. A quantitative analysis of recombination behavior for PERC solar cells and Al-BSF solar cells under different injection levels is very important for process optimization and device modeling. In this paper, incorporating the measured current density–voltage characteristic under different injection levels, the recombination parameters of the diffusion region and the depletion region and their effect on output performance are investigated for Al-BSF silicon solar cells and PERC silicon solar cells for the first time. It is found that the recombination parameter J_{01} of the diffusion region and the recombination parameter J_{02} of the depletion region of PERC solar cells are smaller than those of Al-BSF solar cells under the same injection level. This result shows that a PERC silicon solar cell has high carrier collection efficiency under different injection levels compared with an Al-BSF solar cell. According to the obtained recombination parameters, the current–voltage equation of solar cells can be established under different injection levels, and the daily energy production can be calculated accurately. An interesting finding is that the J_{01} of an Al-BSF solar cell increases quickly with the decreasing injection level compared with a PERC silicon solar cell. This reveals that the output performance of an Al-BSF solar cell decreases rapidly when the injection level is getting low compared with a PERC silicon solar cell. In order to improve the performance of Al-BSF solar cells under low irradiance, the J_{01} must be reduced by decreasing process contamination and good passivation. Finally, the relationship between the J_{01}/J_{02} and injection level for Al-BSF and PERC solar cells is investigated under different injection levels, and the effects of J_{01}/J_{02} on open-circuit voltage, short-circuit current density, and fill factor are also analyzed under different injection levels. The results indicate that the recombination behavior of different cell regions will change with the injection level, and the ratio of J_{01}/J_{02} under different injection levels will affect the output performance of Al-BSF and PERC solar cells. The conclusions obtained in this article not only clarify the relationship between the recombination parameter and injection levels under non-standard test conditions, but also help to optimize solar cell processes and accurately model daily energy production for crystalline silicon solar module energy rating purposes.

2. Experiments and Methods

In this work, the Al-BSF silicon solar cell and PERC silicon solar cell were fabricated by typical industrial processes and production equipment, respectively. The material used in this work was 156.75 mm×156.75 mm boron-doped Czochralski-grown pseudo-square silicon wafers with 1–2 Ω cm base resistivity and an initial wafer thickness of 190 μ m. The area of silicon wafer was 244.3155 cm². After standard cleaning and alkaline texturing, a wet chemical single-sided polishing step, which removes about 4–6 μ m of silicon from the rear surface, was carried out.

The emitter layer of the Al-BSF solar cell was formed in a closed tube furnace using a POCl_3 liquid source at 800 °C. The phosphorus diffusion resulted in a 90–100 Ω/sq emitter with a peak doping concentration of about $2 \times 10^{19} \text{ cm}^{-3}$. The p–n junction depth was about 0.4 μm . After the POCl_3 diffusion, laser doping was carried out so as to form a front selective emitter. The phosphosilicate glass removal, edge isolation, and rear side polishing were fulfilled simultaneously in a Rena wet bench. After a cleaning step, the plasma-enhanced chemical vapor deposition of SiNx:H thin film was used for passivation and anti-reflective purposes on the front side of the solar cell. At last, the screen-printed silver paste back contact, screen-printed aluminum paste back surface field, and silver paste front contact were prepared and co-fired rapidly in a belt furnace made by Centrotherm photovoltaics AG.

For the PERC solar cell, the formation of the emitter layer was the same as that for the Al-BSF solar cell. As the next step in the process, the rear side of the solar cell was passivated with an atomic-layer deposition of AlOx capped with a plasma-enhanced chemical vapor deposition of a SiNx:H thin film. An 80 nm SiNx:H antireflection coating layer was deposited by plasma-enhanced chemical vapor deposition on the front side of the solar cell. Then, the rear contact pattern was formed by laser ablation with a 532 nm ps laser. Screen printing and co-firing were used for front and rear side metallization of the PERC solar cell.

Finally, the electrical performance of the Al-BSF solar cell and the electrical performance of the PERC solar cell were tested by a Gsolar testing system (XJCC-10, AAA class pulsed solar simulator, in accordance with IEC 60904-9, 200–1200 W/m^2 by steps of 100 W/m^2). The light injection level can be calibrated by the reference cell, and can be set via the target voltage. Table 1 lists the measured parameters of the Al-BSF solar cell and the PERC solar cell under standard test conditions (STC: 1 kW/m^2 irradiance, 25 °C module temperature, and AM1.5 global spectrum). In Table 1, η is the conversion efficiency of the solar cell; V_{oc} is the open-circuit voltage; J_{sc} is the short-circuit current density; V_m is the maximum power point voltage; J_m is the maximum power point current density; P_m is the optimal power delivered by the solar cell under STC; FF is the fill factor; and R_s and R_{sh} are the series resistance and the shunt resistance in ohms, respectively. The schematic structures for the Al-BSF solar cell and the PERC solar cell are shown in Figure 1.

Table 1. The measured parameters of the full-area aluminum back surface field (Al-BSF) solar cell and the passivated emitter and rear cell (PERC) solar cell under standard test conditions (STC).

Parameter	η (%)	V_{oc} (V)	J_{sc} (mA/cm^2)	V_m (V)	J_m (mA/cm^2)	P_m (W)	FF (%)	R_s ($\text{m}\Omega$)	R_{sh} (Ω)
Al-BSF solar cell	20.30	0.6426	39.35	0.5454	37.22	4.960	80.28	2.01	334.25
PERC solar cell	22.45	0.6842	40.66	0.5843	38.43	5.486	80.71	2.40	509.76

STC: 1 kW/m^2 irradiance, 25 °C module temperature, and AM 1.5 global spectrum.

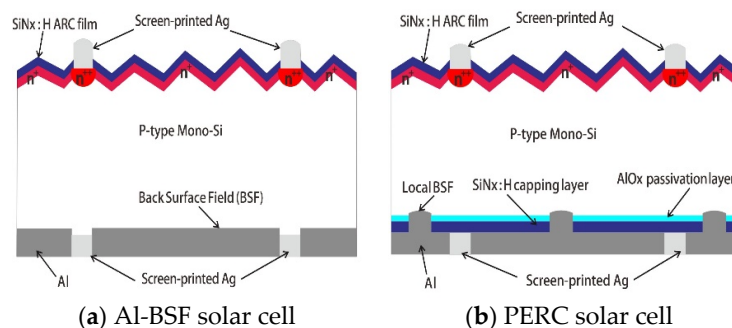


Figure 1. Schematic structures of an Al-BSF solar cell (a) and a PERC solar cell (b).

3. Results and Discussion

3.1. Theoretical Analysis of the Recombination Parameters of the Diffusion Region and Depletion Region for Silicon Solar Cells

The recombination parameter J_{01} of the diffusion region and the recombination parameter J_{02} of the depletion region are distinguished by the double-diode exponential model exactly [38–41]. Figure 2 presents the experimental silicon solar cells and the double-diode model. According to the double-diode model's equivalent circuit, the expression of the current density–voltage (J–V) relationship of the solar cells is given by

$$J = J_{ph} - J_{d1} - J_{d2} - \frac{V + JR_s}{R_{sh}} \quad (1)$$

where

$$J_{d1} = J_{01} \left(\exp \frac{V + JR_s}{n_1 V_T} - 1 \right) \quad (2)$$

$$J_{d2} = J_{02} \left(\exp \frac{V + JR_s}{n_2 V_T} - 1 \right), \quad (3)$$

then

$$J = J_{ph} - J_{01} \left(\exp \frac{V + JR_s}{n_1 V_T} - 1 \right) - J_{02} \left(\exp \frac{V + JR_s}{n_2 V_T} - 1 \right) - \frac{V + JR_s}{R_{sh}} \quad (4)$$

where V_T is the thermal voltage, $V_T = kT/q$; k is the Boltzmann constant; q is the electronic charge in coulombs; T is the temperature in degrees Kelvin; n_1 and n_2 are quality factors in the quasi-neutral region and in the space-charge region, respectively; V is the applied forward bias in volts; and J_{ph} is the photo-generated current density, which is nearly equal to J_{sc} .

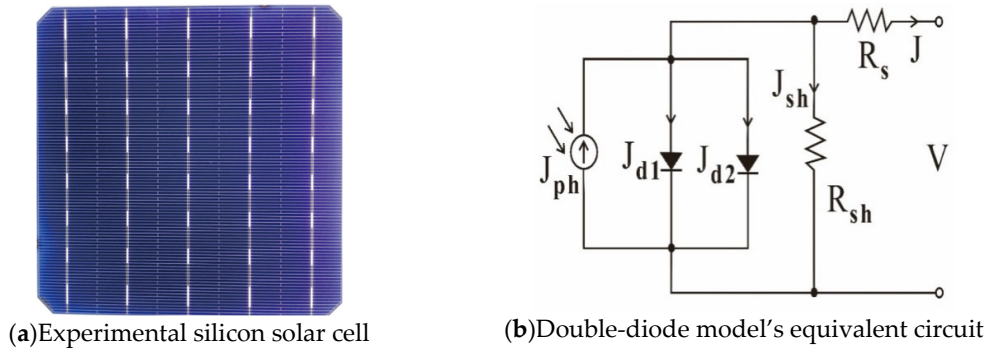


Figure 2. The experimental silicon solar cell and the double-diode model.

For calculating the recombination parameter J_{01} of the diffusion region and the recombination parameter J_{02} of the depletion region, we used the current density and voltage at the maximum power point, at the short-circuit point, and at the open-circuit point. Equations (2) and (3) can be obtained as follows:

$$J_{01} = \frac{\left(J_{sc} - J_m - \frac{V_m + J_m R_s}{R_{sh}} \right) \left(\exp \frac{V_{oc}}{n_2 V_T} - 1 \right) - \left(J_{sc} - \frac{V_{oc}}{R_{sh}} \right) \left(\exp \frac{V_m + J_m R_s}{n_2 V_T} - 1 \right)}{\left(\exp \frac{V_m + J_m R_s}{n_1 V_T} - 1 \right) \left(\exp \frac{V_{oc}}{n_2 V_T} - 1 \right) - \left(\exp \frac{V_m + J_m R_s}{n_2 V_T} - 1 \right) \left(\exp \frac{V_{oc}}{n_1 V_T} - 1 \right)} \quad (5)$$

$$J_{02} = \frac{\left(J_{sc} - J_m - \frac{V_m + J_m R_s}{R_{sh}} \right) \left(\exp \frac{V_{oc}}{n_1 V_T} - 1 \right) - \left(J_{sc} - \frac{V_{oc}}{R_{sh}} \right) \left(\exp \frac{V_m + J_m R_s}{n_1 V_T} - 1 \right)}{\left(\exp \frac{V_m + J_m R_s}{n_2 V_T} - 1 \right) \left(\exp \frac{V_{oc}}{n_1 V_T} - 1 \right) - \left(\exp \frac{V_m + J_m R_s}{n_1 V_T} - 1 \right) \left(\exp \frac{V_{oc}}{n_2 V_T} - 1 \right)} \quad (6)$$

The J_{01}/J_{02} ratio can be derived by Equations (5) and (6).

$$\frac{J_{01}}{J_{02}} = \frac{\left(J_{sc} - J_m - \frac{V_m + J_m R_s}{R_{sh}} \right) \left(\exp \frac{V_{oc}}{n_2 V_T} - 1 \right) - \left(J_{sc} - \frac{V_{oc}}{R_{sh}} \right) \left(\exp \frac{V_m + J_m R_s}{n_2 V_T} - 1 \right)}{\left(J_{sc} - \frac{V_{oc}}{R_{sh}} \right) \left(\exp \frac{V_m + J_m R_s}{n_1 V_T} - 1 \right) - \left(J_{sc} - J_m - \frac{V_m + J_m R_s}{R_{sh}} \right) \left(\exp \frac{V_{oc}}{n_1 V_T} - 1 \right)} \quad (7)$$

For an eligible solar cell, R_{sh} is sufficiently large, and the $(V_m + J_m R_s)/R_{sh}$ and V_{oc}/R_{sh} terms can be neglected. Usually, V_{oc} is large enough so that $V_{oc}/(n_2 V_T)$ and $V_{oc}/(n_1 V_T)$ are very much larger than unity at 300 K or so. Since the $\exp[V_{oc}/(n_2 V_T)]$ and $\exp[V_{oc}/(n_1 V_T)]$ variables are far greater than 1, the factor of unity in the brackets can be neglected. So, the J_{01}/J_{02} ratio can be written as:

$$\frac{J_{01}}{J_{02}} = \frac{(J_{sc} - J_m) \exp \frac{V_{oc}}{n_2 V_T} - J_{sc} \exp \frac{V_m + J_m R_s}{n_2 V_T}}{J_{sc} \exp \frac{V_m + J_m R_s}{n_1 V_T} - (J_{sc} - J_m) \exp \frac{V_{oc}}{n_1 V_T}} \quad (8)$$

If the current density–voltage relationships of an Al-BSF solar cell and a PERC solar cell can be measured under different injection levels, the relationships between J_{01}/J_{02} and open-circuit voltage, short-circuit current, and fill factor can be obtained according to Equation (8).

In our analytical method, the root mean square error (RMSE) of current density was used to compare the variation in simulation accuracy. The RMSE of current density is defined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^m (J_{meas}^i - J_{cal}^i)^2}{m}} \quad (9)$$

where J_{meas} and J_{cal} are the measured and calculated values of output current density in point i , respectively, and m is the number of points.

Figure 3 illustrates the flowchart to find J_{01} and J_{02} under different injection levels. In this work, R_s and R_{sh} under different injection levels are given by the measured values. It is necessary to assign good initial values for solving the above nonlinear Equations (1–8). When the root mean square error (RMSE) of current density gets to its minimum, the accuracy of the entire curve is satisfied, and the calculated J_{01} and J_{02} under different injection levels are derived.

Table 2 shows the J_{01} , J_{02} , and RMSE of current density for an Al-BSF solar cell at typical injection levels. Table 3 lists the J_{01} , J_{02} , and RMSE of current density for a PERC solar cell at typical injection levels. From Table 2 and Table 3, it is found that the RMSE of current density is less than 1% for the Al-BSF solar cell and the PERC solar cell at typical injection levels. These results suggest that the difference between calculated and experimental data is very small, and the obtained J_{01} and J_{02} values could reveal the recombination behavior of the diffusion region and depletion region for Al-BSF solar cells and PERC solar cells at typical injection levels.

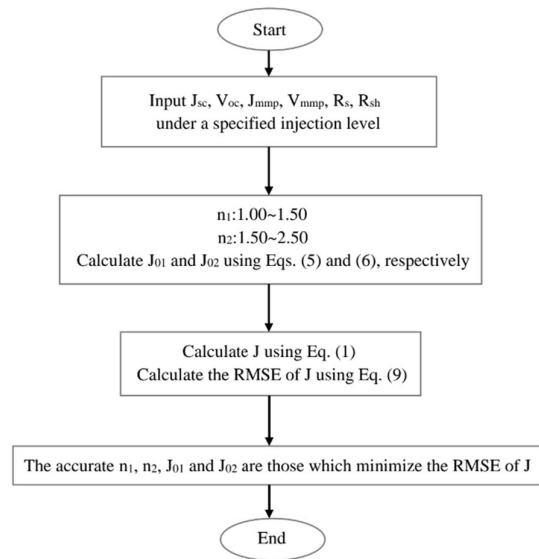


Figure 3. Flowchart to find the J_{01} and J_{02} under different injection levels.

Table 2. The J_{01} , J_{02} , and root mean square error (RMSE) of current density for an Al-BSF solar cell.

Injection Level (W/m ²)	200	400	600	800	1000	1200
RMSE (%)	0.73	0.62	0.48	0.36	0.39	0.42
J_{01} ($\times 10^{-12}$ A/cm ²)	1.9440	1.8401	1.7220	1.6223	1.5442	1.4404
J_{02} ($\times 10^{-8}$ A/cm ²)	0.2034	0.3257	0.4519	0.6599	1.5564	2.7720

25 °C cell temperature and AM 1.5 global spectrum.

Table 3. The J_{01} , J_{02} , and RMSE of current density for a PERC solar cell.

Injection Level (W/m ²)	200	400	600	800	1000	1200
RMSE (%)	0.68	0.59	0.45	0.36	0.38	0.41
J_{01} ($\times 10^{-12}$ A/cm ²)	0.2698	0.2501	0.2311	0.2135	0.1887	0.1805
J_{02} ($\times 10^{-8}$ A/cm ²)	0.0612	0.0790	0.0997	0.1664	0.4962	0.9863

25 °C cell temperature and AM 1.5 global spectrum.

Figure 4 displays a comparison of the RMSE of current density for an Al-BSF solar cell and a PERC solar cell under different injection levels. From Figure 4, it can be seen that the RMSEs of current density for the Al-BSF solar cell and the PERC solar cell are nearly the same according to our analytical method under different injection levels. The results show that J_{01} and J_{02} could be used to explain discrepancies in recombination behavior for the Al-BSF solar cell and the PERC solar cell under different injection levels.

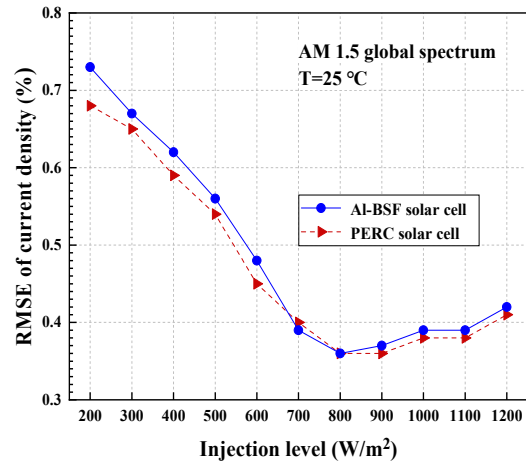


Figure 4. Comparison of the RMSE of current density for an Al-BSF solar cell and a PERC solar cell under different injection levels.

3.2. Investigation into the Recombination Parameters of the Diffusion Region and Depletion Region for a PERC Silicon Solar Cell and an Al-BSF Silicon Solar Cell under Different Injection Levels

The relationship between J_{01} and the injection level at 25 °C and AM1.5G for the Al-BSF solar cell and the PERC solar cell is depicted in Figure 5. From Figure 5, it is found that the J_{01} of a PERC solar cell is always lower than that of an Al-BSF solar cell no matter how much the injection level changes. These results suggest that a PERC solar cell has higher carrier collection efficiency under different injection levels compared with an Al-BSF solar cell. As observed, the J_{01} of the Al-BSF solar cell was 1.54×10^{-12} A/cm² under STC, but the J_{01} of the PERC solar cell was only 1.89×10^{-13} A/cm² under STC. This is because a PERC solar cell with AlO_x and SiN_x:H rear passivation has a lower back surface recombination velocity compared with an Al-BSF solar cell. This result agrees with other authors' works [42–44]. A new finding is that the J_{01} of an Al-BSF solar cell increases quickly with the decreasing injection level compared with a PERC silicon solar cell. These results reveal that the output performance of an Al-BSF solar cell decreases rapidly when the injection level is getting low compared with a PERC silicon solar cell.

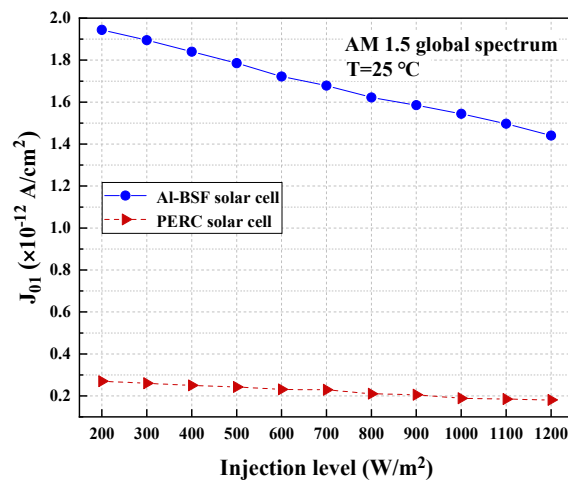


Figure 5. J_{01} versus injection level for an Al-BSF solar cell and a PERC solar cell at 25 °C and AM1.5G.

Figure 6 shows the comparison of J_{02} for these two kinds of solar cells at 25 °C and AM1.5G. From Figure 6, it is found that the J_{02} of Al-BSF and PERC solar cells increase with the increasing injection level. This is because the effective minority carrier lifetime in the depletion region decreases

sharply in high injection levels [45, 46]. Meanwhile, owing to rear passivation, the J_{02} of PERC solar cell is always lower than that of Al-BSF solar cells under the same injection level. It is also observed that the J_{02} variation of a PERC solar cell is significantly smaller than that of an Al-BSF solar cell as the injection level is varied from 200 W/m² to 1200 W/m². Specifically, when the injection level increases from 900 W/m² to 1200 W/m², the J_{02} of a PERC solar cell increases from 2.94×10^{-9} A/cm² to 9.86×10^{-9} A/cm², but the J_{02} of an Al-BSF solar cell increases rapidly from 9.12×10^{-9} A/cm² to 2.77×10^{-8} A/cm². The obtained result agrees with other publications [47, 48].

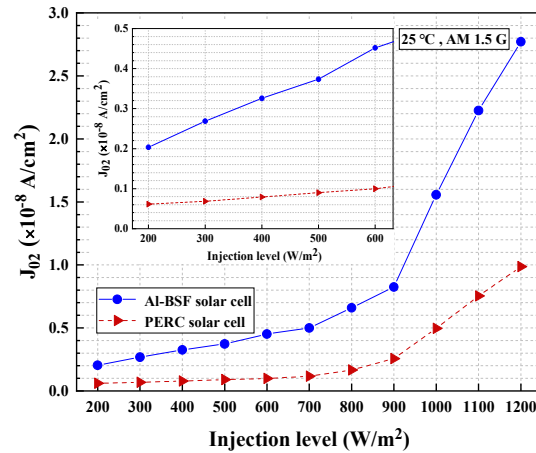


Figure 6. J_{02} of an Al-BSF solar cell and a PERC solar cell as a function of the injection level at 25 °C and AM1.5G.

Figure 7 describes the variation in the J_{01}/J_{02} ratio of an Al-BSF solar cell and a PERC solar cell as a function of the injection level at 25 °C and AM1.5G. As can be seen from Figure 7, it is found that both the J_{01}/J_{02} ratio of the Al-BSF solar cell and the J_{01}/J_{02} ratio of the PERC solar cell increase with the decreasing injection level. This is because the low injection level leads to a small J_{02} value. These results suggest that J_{02} could be neglected only at a low injection level. Whether it is under high injection or under low injection, the J_{01}/J_{02} ratio of a PERC solar cell is always smaller than that of an Al-BSF solar cell under the same injection level. Moreover, the J_{01}/J_{02} ratio of a PERC solar cell increases slowly with the decreasing injection level compared with an Al-BSF solar cell. These results show that a PERC solar cell performs well when the injection level varies from low to high compared with an Al-BSF solar cell [46].

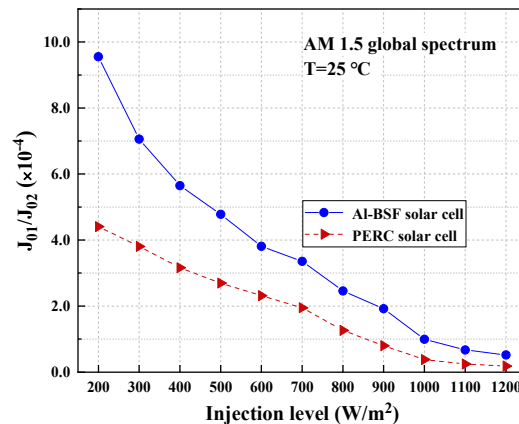


Figure 7. Variation in J_{01}/J_{02} of an Al-BSF solar cell and a PERC solar cell as a function of injection level at 25 °C and AM1.5G.

3.3. Effect of J_{01}/J_{02} on Electrical Parameters of PERC Silicon Solar Cells and Al-BSF Silicon Solar Cells under Different Injection Levels

The relative magnitude of the recombination parameter of the diffusion region and the recombination parameter of the depletion region can be expressed by the J_{01}/J_{02} ratio. Figure 8 shows the variation in open-circuit voltage with the J_{01}/J_{02} ratio for PERC and Al-BSF silicon solar cells under different injection levels. From Figure 8, it is clearly observed that the open-circuit voltages of PERC and Al-BSF silicon solar cells are strongly influenced by the J_{01}/J_{02} ratio, i.e., the open-circuit voltages of these two silicon solar cells increase with the decreasing J_{01}/J_{02} ratio. It is also found that the open-circuit voltages of PERC silicon solar cells are larger than those of Al-BSF silicon solar cells at the same injection level. That is because the PERC structure featuring an AlO_x dielectric rear passivation can decrease the total recombination parameter compared with Al-BSF silicon solar cells. The smaller the recombination parameter, the higher the open-circuit voltage of a solar cell [49–51].

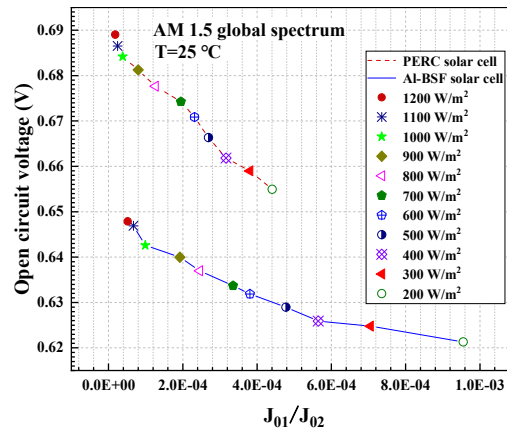


Figure 8. Variation in open-circuit voltage (V_{oc}) with the J_{01}/J_{02} ratio for PERC and Al-BSF silicon solar cells under different injection levels.

Figure 9 depicts the effect of the J_{01}/J_{02} ratio on short-circuit current density (J_{sc}) for PERC and Al-BSF silicon solar cells under different injection levels. As can be seen from Figure 9, as the J_{01}/J_{02} ratio decreases and the injection level is varied from 200 W/m² to 1200 W/m², the J_{sc} of PERC silicon solar cells increases more quickly than that of Al-BSF silicon solar cells at 25 °C. This is because the PERC solar cell has a higher carrier collection efficiency compared with Al-BSF solar cells.

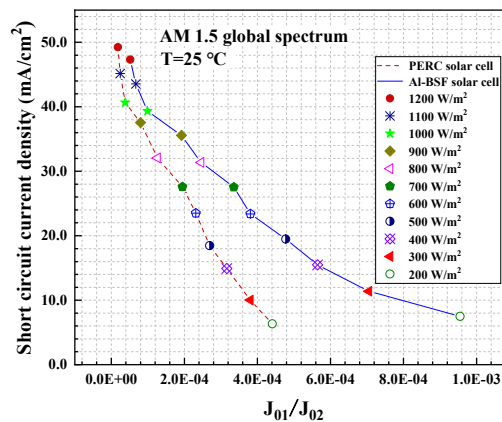


Figure 9. Effect of the J_{01}/J_{02} ratio on short-circuit current density (J_{sc}) for PERC and Al-BSF silicon solar cells under different injection levels.

Figure 10 shows the variation in FF with the J_{01}/J_{02} ratio for PERC and Al-BSF silicon solar cells under different injection levels. The fill factors of PERC and Al-BSF silicon solar cells decrease with the decrease in J_{01}/J_{02} . At the same temperature and injection level, the FF of a PERC silicon solar cell is always higher than that of an Al-BSF silicon solar cell. This result agrees with [52].

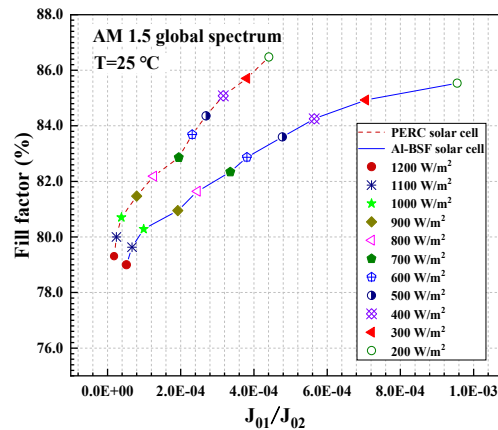


Figure 10. Variation in fill factor (FF) with the J_{01}/J_{02} ratio for PERC and Al-BSF silicon solar cells under different injection levels.

4. Conclusions

The recombination parameters of crystalline silicon solar cells are dependent on the excess carrier concentration. In order to improve the collection efficiency of photo-generated carriers, and to model exactly the performance of solar cells in the field, it is very important to investigate the recombination parameters of solar cells under different injection levels. In this work, the recombination parameters of different regions were investigated under different injection levels for Al-BSF and PERC silicon solar cells. As expected, the recombination parameter J_{01} of the diffusion region and the recombination parameter J_{02} of the depletion region for PERC solar cells are smaller than those of Al-BSF solar cells at the same injection level. An interesting finding is that the recombination parameter J_{01} of Al-BSF solar cells increases quickly with the decreasing injection level compared with PERC silicon solar cells. It can be concluded that the output performance of Al-BSF solar cells decreases rapidly at low injection levels compared with PERC solar cells. Finally, the J_{01}/J_{02} ratio of the Al-BSF solar cell and the J_{01}/J_{02} ratio of the PERC solar cell were investigated under different injection levels. The effects of the J_{01}/J_{02} ratio on open-circuit voltage, short-circuit current density, and fill factor were also analyzed for Al-BSF and PERC solar cells under different injection levels. The results show that the recombination behavior of different cell regions will change with the injection level, and the output performance of Al-BSF and PERC solar cells is affected by the ratio of J_{01}/J_{02} under different injection levels. The conclusions obtained in this paper not only clarify the relationship between the recombination parameters and injection levels under non-standard test conditions, but also help to improve solar cell processes and accurately model daily energy production for crystalline silicon solar module energy rating purposes.

Research is underway at our institute to find the differences in recombination parameters between PERC and Al-BSF silicon solar cells under different temperatures.

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