Analysis of Chromatic Aberration Effects in Triple-Junction Solar Cells Using Advanced Distributed Models

Iván García, Pilar Espinet-González, Ignacio Rey-Stolle, and Carlos Algora, *Senior Member, IEEE*

***Abstract*—The consideration of real operating conditions for the design and optimization of a multijunction solar cell receiver–concentrator assembly is indispensable. Such a requirement involves the need for suitable modeling and simulation tools in order to complement the experimental work and circumvent its well-known burdens and restrictions. Three-dimensional distributed models have been demonstrated in the past to be a powerful choice for the analysis of distributed phenomena in single- and dual-junction solar cells, as well as for the design of strategies to minimize the solar cell losses when operating under high concentrations. In this paper, we present the application of these models for the analysis of triple-junction solar cells under real operating conditions. The impact of different chromatic aberration profiles on the short-circuit current of triple-junction solar cells is analyzed in detail using the developed distributed model. Current spreading conditions the impact of a given chromatic aberration profile on the solar cell *I–V* curve. The focus is put on determining the role of current spreading in the connection between photocurrent profile, subcell voltage and current, and semiconductor layers sheet resistance.**

***Index Terms*—Concentrator photovoltaics (CPV), chromatic aberration, distributed model, multijunction solar cell.**

I. Introduction

TRIPLE-JUNCTION solar cell efficiencies exceeding 40% obtained in recent years combined with high concentrations of 1000 suns and above can make the concentrator photovoltaic (CPV) technology cost competitive for the mass production of electricity, according to many cost analyses [1]. To attain these efficiencies at such high concentrations, one must pay special attention to series resistance-related losses. Moreover, the optical architectures that are used in practical concentrator systems produce nonuniform light irradiance profiles and chromatic aberration in the concentrated light spot impinging on the solar cell. This implies additional losses in the solar cell performance [2], [3]. All these issues are to be tackled during the solar cell development process in order to optimize its performance. However, addressing these issues via exclusively experimental work is time consuming and not cost effective. Consequently, the use of modeling and simulation is unquestionably advantageous. Besides, the use of 3-D models is required for concentrator solar cell applications in order to account for the distributed nature of the light spot which normally exhibits nonuniform irradiance and chromatic aberration.

In this context, 3-D models based on distributed circuit units are an easy-to-use and powerful tool to study the electrical characteristics of any semiconductor device, where solar cells are a particular case [4]. The suitability of these models has been demonstrated for single- and dual-junction concentrator solar cells under uniform and nonuniform irradiance profiles [5], [6]. Recently, we have presented the extension and validation of these models to be able to simulate triple-junction solar cells under real conditions, including nonuniform irradiance profiles and chromatic aberration [7]. One of the strengths of this modeling approach is the ability to probe the currents and voltages at any point of the solar cell equivalent circuit. This allows us to analyze the internal current flows, to plot voltage maps at different bias conditions, etc., making it a powerful tool to assist in the understanding of the effect of real working conditions on the performance of the solar cell. This is illustrated in this paper with an example of such analysis. Particularly, we focus on the effect of chromatic aberration on the *I–V* curve of the triple-junction solar cell and the impact of the lateral current conduction paths characteristics on the current spreading generated.

II. Triple-Junction Solar Cell 3-D Distributed Model

In the modeling approach developed, an equivalent circuit of the whole solar cell is generated. For this, the steps followed are as follows: 1) definition of the solar cell geometry; 2) division of its area into sufficiently small sections, according to the minimum feature size in each part of the solar cell area; 3) assignment of an equivalent circuit to each section (according to its characteristics); 4) definition of the light spot characteristics, including nonuniform irradiance distributions, chromatic aberration, etc.; and 5) finally, generation of the whole solar cell equivalent circuit by connecting all the sections through their lateral current conduction path resistors. Extended details on this procedure can be found elsewhere [4]. The different regions in the solar cell area which are distinguished are as follows: 1) perimeter; 2) metal-covered; and 3) exposed regions. For each

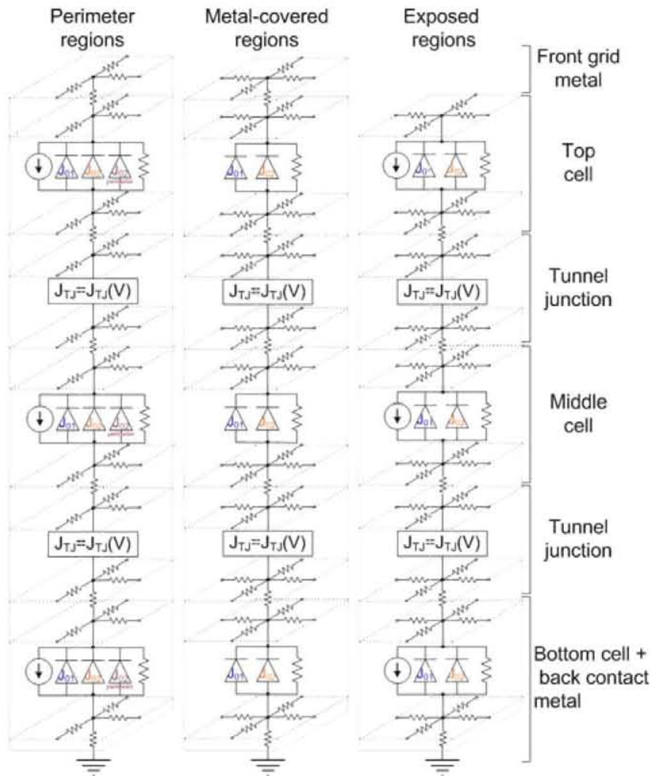

Fig. 1. Equivalent circuit model for the three regions of the solar cell considered in the triple-junction solar cell model used in this study.

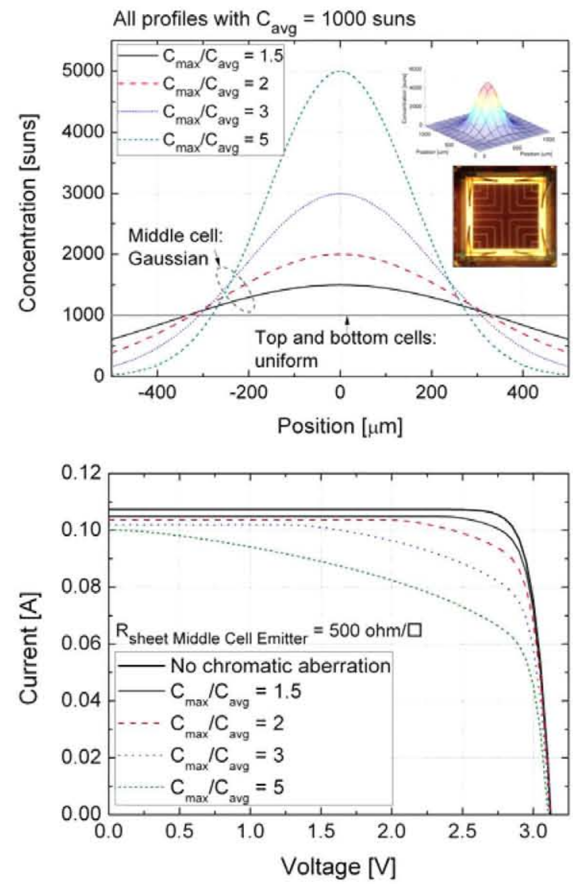

Fig. 2. (Top) Subcell concentration profiles used (uniform for the top and bottom subcells and Gaussian for the middle cell), which correspond to different chromatic aberration patterns generated by the optics of a hypothetical concentrator assembly. (Bottom) Effect of these photocurrent profiles on the triple-junction solar cell *I–V* curve.

of these, the equivalent circuits that we use are shown in Fig. 1. As compared with previous dual-junction solar cell models that were developed by us, we have introduced an additional non-p junction for the bottom cell and an *I–V* characteristic description for the second tunnel junction of the triple-junction solar cell. Moreover, an extended definition of lateral current conduction paths has been implemented, as can be observed in Fig. 1, consisting on adding lateral resistors in all emitter and base layers, and more importantly in both sides of the tunnel junctions. This is key in accurately accounting for current spreading in the solar cell semiconductor structure and, hence, the effect of chromatic aberration in the light spot.

The generation of the whole solar cell equivalent circuit is important for being able to take into account any kind of nonuniformities in the solar cell and in the light spot characteristics, without being restricted to use approximations based on symmetries in these characteristics. Equivalent circuits with a number of nodes and components in the order of the hundreds of thousands are generated for our 1-mm^2 solar cells. The generation and handling of such big equivalent circuits are made possible by the use of a proprietary software.

The validation of this model was presented in [7]. For this, the experimental characterization results obtained for triple-junction solar cells developed in our laboratory, whose technological parameters are well characterized, were compared with the simulation results that are obtained for the same conditions. Particularly, illumination conditions including different spatial and spectral inhomogeneities were used. An excellent agreement between experimental and simulation results was obtained, which demonstrates the validity of this model for the analysis of the electrical performance of the triple-junction solar cell, including the cases where real light spot characteristics are used.

III. Application to Analysis of Chromatic Aberration Effects

The spatially nonuniform current mismatch, which is generated in multijunction solar cells by chromatic aberration, can eventually give rise to conversion efficiency losses. Therefore, it is interesting to analyze how chromatic aberration affects the electrical performance of the solar cell. In this paper, we use an example light spot exhibiting chromatic aberration such that the photocurrent distribution in the top cell (TC) and bottom cell (BC) of the triple-junction solar cell corresponds to a 1000-sun uniform irradiance profile (assuming $J_{\rm sc,1sun} = 14$ mA/cm^2). For the middle cell (MC), we use an irradiance distribution corresponding to the Gaussian profiles shown in Fig. 2 (top). A range of peak-to-average concentration values is used to cover the majority of the cases corresponding to practical optics that generate different chromatic aberration levels. Note that the average photocurrent corresponds in all these Gaussian profiles to a concentration of, again, 1000 suns. This means that the total photocurrent in the TC, MC, and BC is always the same. Since we assume linearity between irradiance and photocurrent in the subcells, we will refer to the irradiance profiles that are shown in Fig. 2 as “MC photocurrent profiles” hereinafter. The modeling and simulation results that are presented in this study correspond to a 1-mm^2 active area triple-junction solar cell with inverted square front grid, as depicted in the inset of Fig. 2 (top). It must be noted that the cell size or front grid geometry does not affect the result of the qualitative study that is presented here. The parameters of the triple-junction solar cell simulated are those corresponding to the devices developed in our laboratory, which are described elsewhere [8].

A. Effect of Chromatic Aberration on the I–V Curve

In the graph shown in Fig. 2 (bottom), the effect of the photocurrent distribution peak-to-average ($C_{\max}/C_{\text{avg}}$) ratio in the MC, on the simulated *I–V* curve of the triple-junction solar cell, is depicted. As can be observed, the fill factor (FF) and short-circuit current (I_{sc}) are the two parameters that are most predominantly affected. The result is an important drop in the solar cell efficiency. It is interesting to note that the variations in I_{sc} and FF that are observed in Fig. 2 (bottom) cannot be explained by the influence of the different spatial current matching distribution generated by each photocurrent profile used for the MC. In fact, as the $C_{\max}/C_{\text{avg}}$ ratio of the MC photocurrent distribution increases, the cumulated current mismatch over the solar cell area increases, and thus, a considerable I_{sc} drop and an increased FF would be predicted. As observed in Fig. 2 (bottom), the result is just the contrary to this expected result. This is because of the effect of current spreading occurring in the solar cell semiconductor structure. Works can be found in the literature dealing with current spreading effect [9], [10]. In our study, we learnt that taking into account the photocurrent matching at each point of the solar cell area to assess the effect of chromatic aberration on the I_{sc} and FF is not correct, because of the effect of current redistribution. An “overall” current matching in the solar cell must be considered instead, which is much more favorable for the total I_{sc} in the triple-junction solar cell, but that give rise to a lower FF. This is illustrated in Fig. 3, where the effect of the MC photocurrent distribution on the I_{sc} and FF is shown for the cases of a realistic and a very high MC emitter sheet resistance r_{sh}. For a very high r_{sh}, the lateral current flow is not allowed and the I_{sc} and FF behave as described earlier: The I_{sc} decreases strongly with the $C_{\max}/C_{\text{avg}}$ ratio of the MC photocurrent distribution, and the FF increases with respect to the case without chromatic aberration. For a realistic MC emitter r_{sh}, current redistribution occurs, and the I_{sc} is affected by the $C_{\max}/C_{\text{avg}}$ ratio but to a much lesser extent. However, the FF is affected markedly, as was already observed in Fig. 2. The effect of the lateral current flow on the I_{sc} and FF, and its dependence on the lateral resistance, is studied in the following sections.

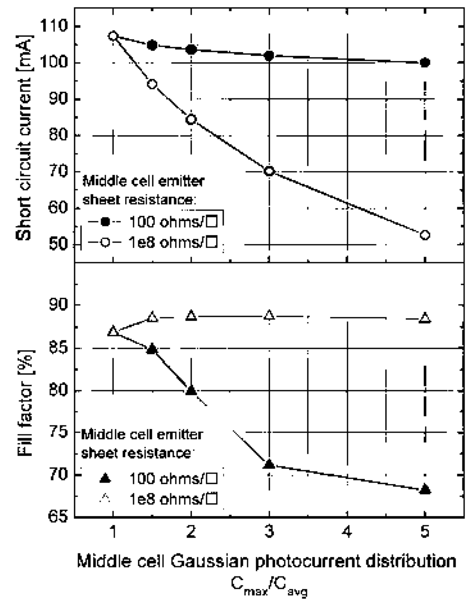

Fig. 3. Simulated short-circuit current and FF against the $C_{\max}/C_{\text{avg}}$ ratio of the middle cell photocurrent distribution for a realistic and a very high middle cell emitter sheet resistance.

B. Influence of Lateral Current Flow on the I_{sc}

Ideally, if no obstacle would exist for lateral current spreading in a multijunction solar cell, the effect of chromatic aberration on its I_{sc} would be negligible. However, in practice, this lateral current flow takes place through layers with a nonzero sheet resistance. This sheet resistance and the voltage distribution in the solar cell area, which is determined by the solar cell and light spot properties, define these lateral current flows. For example, at certain regions of the solar cell, the voltage distribution may cause that the excess photocurrent generated in the MC flows toward regions where the MC photocurrent is lower than the TC photocurrent. This way, it can contribute to the overall triple-junction solar cell I_{sc}. In the opposite case, this excess photocurrent is “wasted” by recombination because of a higher MC voltage in that region of the solar cell. Therefore, the possibility for current to flow laterally influences the impact of chromatic aberration on the I_{sc}.

The 3-D distributed model that we have developed was used to analyze these effects. Some simulation results obtained are shown in Fig. 4. First, the normalized I_{sc} of the triple-junction solar cell was plotted against the MC emitter r_{sh}, for the chromatic aberration profiles studied [indicated in Fig. 2 and in the inset of Fig. 4 (left-top)]. Although typical values of r_{sh} in practical devices range from 100 to 1000 Ω/□, a wider range has been swept to make effects more clear. As can be observed, as the aspect ratio in the Gaussian photocurrent profile used for the MC is increased, the emitter r_{sh} needed to keep the solar cell I_{sc} unaffected by the chromatic aberration is lower. Moreover, the influence of the current redistribution on the mitigation of the effect of chromatic aberration on the I_{sc} can be inferred from this graph. For the cases with artificially high r_{sh}, no lateral current flow exists, and the I_{sc} drop due to chromatic aberration is much higher than for the cases with a low r_{sh} when lateral

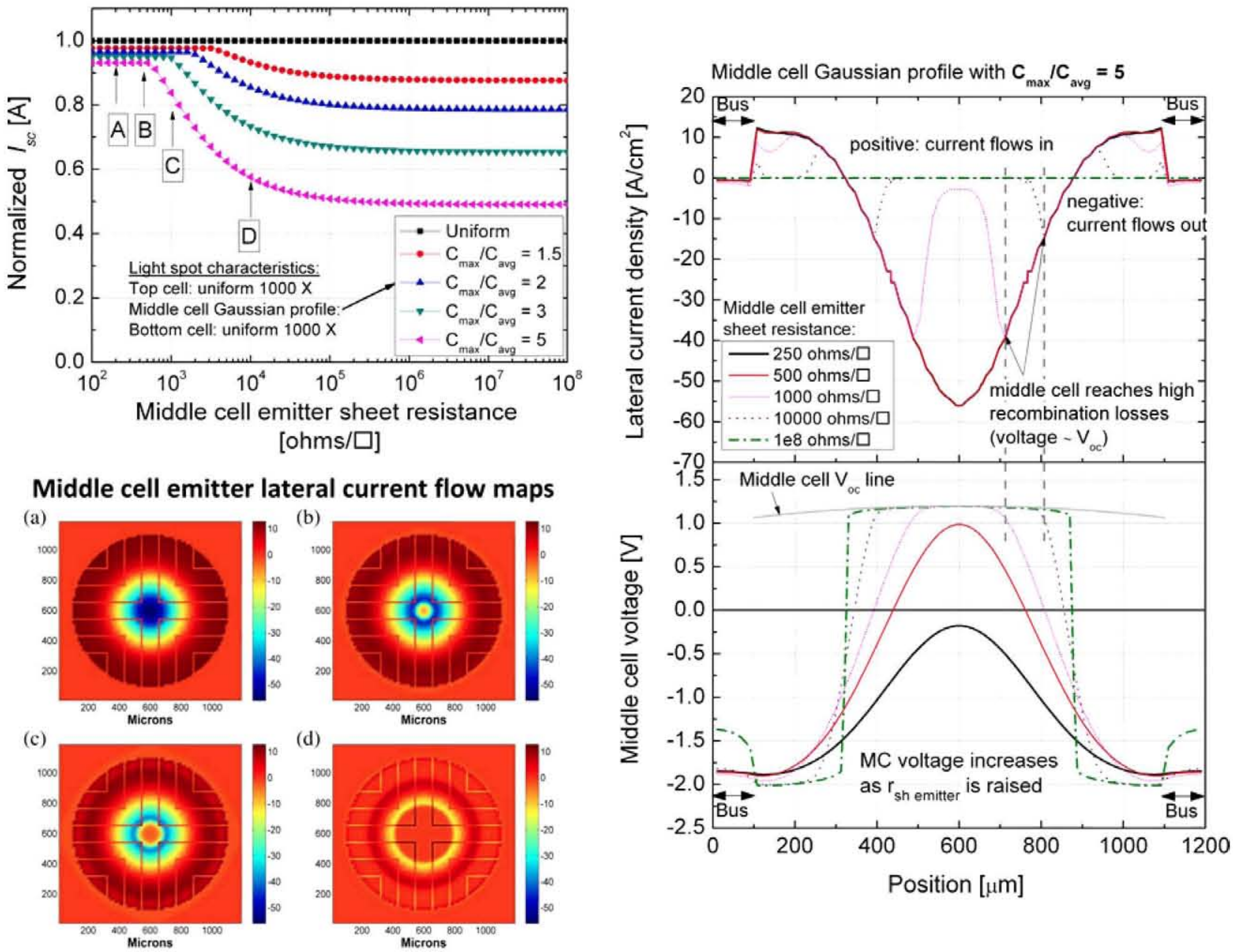

Fig. 4. (Left-top) Triple-junction solar cell normalized I_{sc} against middle cell emitter sheet resistance for the different chromatic aberration profiles studied. (Left-bottom) False color plots of the current spreading at middle cell emitter level for the cases labeled in left-top graph. (Right) Cross section of the lateral current spreading at middle cell emitter level, and middle cell voltage, taken transversally at the center of the solar cell device for the case of $C_{max}/C_{avg} = 5$ in the Gaussian photocurrent profile of the middle cell. In all these figures, the triple-junction solar cell is at short circuit.

current flow takes place. The false color maps shown below this graph represent the current spreading at the MC emitter level, for the cases indicated in the graph on the top-left. A 0 value means no current spreading. A negative current indicates that in this region of the solar cell, current is flowing away through the MC emitter to cross the tunnel junction toward other subcell at other region of the solar cell with a lower MC photocurrent, and vice versa for positive currents. As can be observed, the integrated lateral current flow over the solar cell area decreases as the MC emitter r_{sh} increases.

The influence of the MC emitter r_{sh} on the I_{sc} starts to be noticed abruptly for a certain value of this r_{sh}, as can be observed in Fig. 4 (top-left). The reason for this was analyzed using the cross-sectional graphs shown in Fig. 4 (right). The upper graph shows the current spreading at the MC emitter level and the lower graph shows the MC voltage. In both cases, the results that are obtained for different MC emitter r_{sh} are shown. The meaning of the sign in the current spreading graph is the same as that explained for the false color plots.

As the MC emitter r_{sh} is increased, the voltage at the MC increases, as can be observed. For a given value of this r_{sh}, some regions of the solar cell have its MC biased at a voltage close to the V_{oc} corresponding to its irradiance level (indicated as "middle cell V_{oc} line" in the graph). At this voltage, the recombination current increases exponentially in these regions, causing less current to be available for supply to other regions of the solar cell with a lower photocurrent in the MC. This is evidenced by the dip observed in the MC lateral current density plots. As a consequence, the total I_{sc} of the triple-junction solar cell starts to decrease. As the MC emitter r_{sh} is further increased, larger regions of the solar cell area are in this situation, and therefore, the triple-junction solar cell I_{sc} decreases more, which is in agreement with the results shown in Fig. 4 (left-top). For a very high MC emitter r_{sh}, no current spreading can take place and the excess current photogenerated in the regions of the MC with a higher irradiance is lost by recombination. Similarly, the excess current in the TC and BC in the peripheral regions, where the Gaussian profile in the MC is below 1000 suns, is also lost. In this situation, the I_{sc} of the triple-junction solar cell is defined purely by the sum of the minimum current in the top, middle, and bottom subcells at each point in the area of the solar cell.

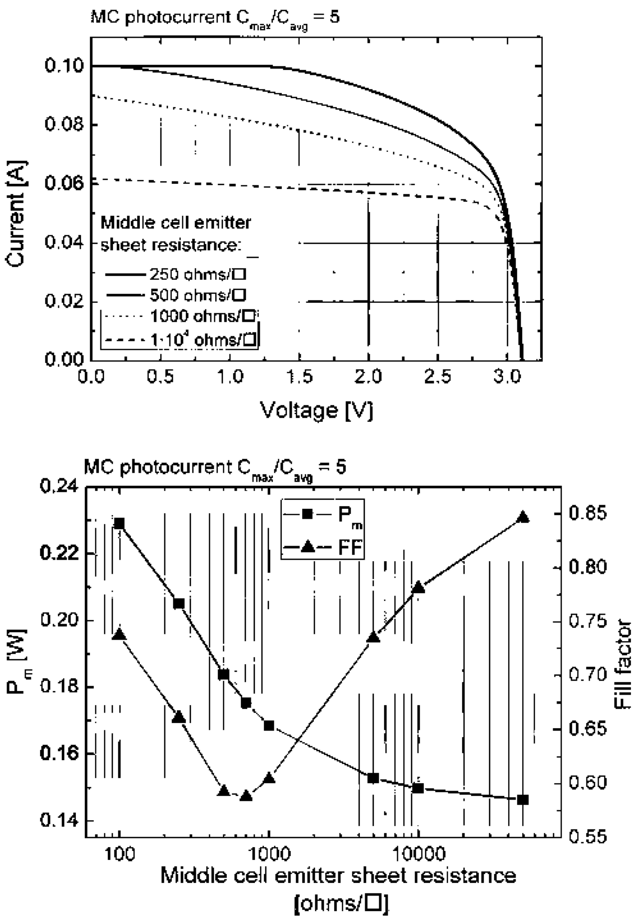

Fig. 5. (Top) Simulated *I–V* curves of the triple-junction solar cell for different MC emitter $r_{\rm sh}$. (Bottom) $I_{\rm sc}$ and FF against the MC emitter $r_{\rm sh}$. In both plots, $C_{\rm max}/C_{\rm avg} = 5$ in the Gaussian photocurrent distribution of the MC.

C. Influence of Lateral Current Flow on the Fill Factor

Intuitively, the introduction of chromatic aberration in the light spot impinging a multijunction solar cell should give rise to a higher FF because of the photocurrent mismatch generated. However, this is not observed in practice, as shown in Fig. 3, because of the existence of lateral current flows inside the semiconductor structure of the solar cell, as explained in former sections. Moreover, not only does not the FF increase, but it drops significantly as the aspect ratio of the chromatic aberration profile is made higher, as can be seen in Fig. 3.

In order to analyze the effect of the lateral current flow on the FF, in Fig. 5, the effect of increasing the MC emitter $r_{\rm sh}$ on the *I–V* curve of the triple-junction solar cell is shown. The $r_{\rm sh}$ values used correspond to points labeled A to D in Fig. 4 (top-left). In the graph at the bottom, the evolution of the FF and maximum power P_m with the MC emitter $r_{\rm sh}$ is detailed. Note how the FF first drops but, as soon as this $r_{\rm sh}$ is made sufficiently high so as to affect the $I_{\rm sc}$ of the triple-junction solar cell (see Fig. 4), it starts to increase. This is obviously not due to a change in the mechanisms behind the FF dependence on the MC emitter $r_{\rm sh}$, but to the fact that the FF is not a fundamental parameter but just the ratio between P_m and $V_{\rm oc}{*}I_{\rm sc}$. Actually, the P_m is always decreasing, as can be observed.

For moderate values of $r_{\rm sh}$, the $I_{\rm sc}$ and $V_{\rm oc}$ of the solar cell remain unchanged [see Fig. 4 (top-left) and Fig. 5 (top)], and thus, the FF starts to decrease as a result of the decrease in P_m. At first sight, a possible origin of these losses could be thought to be linked to ohmic voltage drops in the lateral redistribution of current. However, a careful look at the *I–V* curves in Fig. 5 (top) reveals that the slope of all curves near $V_{\rm oc}$—where typically series resistance losses manifest—is essentially the same in all cases.

From this result, it is evident that the mechanism behind the effect of the MC emitter $r_{\rm sh}$ on the shape of the *I–V* curve for a given chromatic aberration profile is not simply the effect of a series resistance-related loss. In fact, for very high MC emitter $r_{\rm sh}$ values, the FF of the solar cell reaches the highest values, which is contrary to the typical effect of a series resistance component.

The explanation for this effect on the shape of the *I–V* curve is connected to that given for the effect on the $I_{\rm sc}$ in last section, which was illustrated with Fig. 4. Fig. 5 (top) shows that for any given voltage, as the MC emitter $r_{\rm sh}$ increases, the current produced by the solar cell decreases. The reason for this is as follows: As the MC emitter $r_{\rm sh}$ increases, higher voltage drops are caused by the lateral current flow and thereby the regions of the solar cell with a higher photocurrent in the MC reach earlier a voltage close to the $V_{\rm oc}$ in the MC junction. In this situation, the recombination current is highly increased in those areas (i.e., the recombination losses increase locally), and therefore, there is less photocurrent available to be delivered by the solar cell.

For moderate values of MC emitter $r_{\rm sh}$, the $I_{\rm sc}$ remains unaffected and the current drop only affects the vicinity of the maximum power point. This explains why the FF decreases initially in Fig. 5 (bottom). For large values of MC emitter $r_{\rm sh}$, the $I_{\rm sc}$—in the denominator of the FF ratio—is greatly diminished, in a higher proportion than the P_m—in the numerator of the FF ratio—and, thus, the FF increase. In this regime, the *I–V* curve of the triple-junction solar cell converges to one with a high FF and a low $I_{\rm sc}$, as corresponds to such a solar cell without lateral current flow.

IV. Conclusion

Using 3-D distributed models of a triple-junction solar cell, the effect of chromatic aberration in the light spot impinging the device has been studied. Chromatic aberration introduces a spatially nonuniform subcell current mismatch in the triple junction solar cell. However, a relatively low $I_{\rm sc}$ drop and an FF decrease were observed to be caused by the example chromatic aberration case analyzed. This unexpected result has been demonstrated to be caused by the current spreading generated in the semiconductor structure, which redistributes the excess current generated in some regions and contributes to achieve a lower "overall" current mismatch in the solar cell. The relation between the $I_{\rm sc}$ loss and FF modifications because of the chromatic aberration profile and the middle cell emitter sheet resistance has been studied by analyzing the distribution of currents and voltages over the solar cell area. As a main conclusion, these effects are related to the enhanced recombination current generated in the middle cell, because of its increased bias voltage caused by the lateral current flow. From this analysis, it can be concluded that enabling lateral current flow as much as possible in the solar cell structure can contribute significantly to reduce the effect of chromatic aberration caused by the optics used. In other words, the design of the semiconductor structure can help mitigate the effect of chromatic aberration produced by a given optics. An optimum solar cell + optics design, concerning performance and cost, can eventually be developed. The 3-D distributed model developed has been demonstrated to be a powerful tool for the analysis of phenomena that affect the performance of triple-junction solar cells under real light conditions. The way each subcell responds to these conditions can be determined and spatially resolved, making possible the analysis of the mechanisms involved and assist the design of actions to be taken in order to mitigate the possible adverse effects on the performance of the solar cell.

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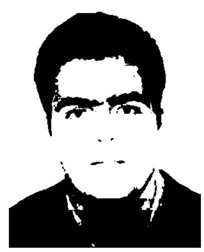

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