Partially shaded III-V concentrator solar cell performance


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ABSTRACT

Currently, an important concern in CPV is inhomogeneity of the light distribution on the cell introduced by the applied optical systems, which may affect system performance. In BICPV applications, the inhomogeneities can be much more severe because of design constraints introduced by the building incorporation. Additionally, one of the predominant loss mechanisms in CPV solar cells is perimeter recombination. In this study, the electrical parameters of CPV cells are investigated under inhomogeneous illumination intensity profiles. Partial shading is used as a model for extremely inhomogeneous illumination, while several shadow patterns are used to study the effect of perimeter recombination on the cell performance. As the latter occurs most strongly in GaAs subcells, shallow and deep junction GaAs CPV cells have been developed and subjected to these experiments, as well as commercial triple junction CPV cells. Deep junction GaAs cells are shown to perform significantly better under concentrated light than their shallow junction counterparts. A large degree of shading exceeding 70% has been found to cause only minor losses in the cell performance of 4%. Also, the cell performance is found to be independent of the location of illumination, in spite of perimeter recombination effects, because the current density spreads out. Clearly, increased illumination inhomogeneities caused by elaborate BICPV optical systems, do not inhibit the electrical performance strongly. As a consequence, a large degree of design freedom exists for the optical systems, which offers good opportunities to develop BICPV that meet all the design challenges of the built environment.

1. Introduction

In the last decades the interest in multi-junction (MJ) solar cells for use in concentrator photovoltaic (CPV) setups has dramatically increased because of their higher conversion efficiency compared to other PV technologies [1]. Still, the demand for higher efficiency cells continues to rise and drive the need for research in MJ solar cell technology. CPV systems aim to deliver electrical power at a lower cost than traditional photovoltaics such as flat Si panels [2,3]. To achieve this goal, maximum performance from the MJ solar cells optimized for concentrators should be obtained, while minimizing the cost of optics, temperature control and other balance-of-system [4]. As demonstrated efficiencies for 3-, 4- and more junction III-V CPV cells continue to rise the chances for economically viable CPV systems are increasing, but this also puts more demands on the concentrating systems. In recent years a noteworthy rise in building integrated photovoltaics has occurred in Europe. These systems contribute to the move towards energy neutral buildings by combining PV in the building design, applying several different integration methods. Examples include full roof systems [5–8], solar Skylights [9,10], solar roof tiles [11,12], rain-screen solar façade [13], and solar curtain wall [14]. A good overview of the current status of BIPV has recently been published by the Solar Energy Application Centre (The Netherlands) and the University of Applied Sciences and Arts of Southern Switzerland [15]. Added functionality in building integrated photovoltaics can be realized through concentrator photovoltaics, in the form of heat generation [16,17] or daylight regulation [18,19].

At present, an important concern in CPV remains the inhomogeneity of the light distribution on the cell introduced by these optical systems [20–28]. This may cause loss of performance due to an increased series resistance, as well as current mismatch between junctions [29]. In BICPV applications in particular, the inhomogeneities can be much more severe than in ‘traditional’, field-based concentrating systems because of the latter being subject to a complex geometry [17,19]. Many concentrator system designs aim to minimize this inhomogeneity by means of a homogenizing Secondary Optical Element (SOE) [30,31]. SOEs can reduce spatial and spectral inhomogeneity via (multiple) internal reflections of the incident light. In addition, a SOE usually adds secondary concentration to a CPV system. In previous work we showed...
the benefit of using a SOE in symmetrical CPV systems [32]. However it is also noted that for asymmetric systems the use of a SOE might be detrimental to the overall device performance. As many CPV systems do not apply a SOE it remains important to gain a better understanding of the solar cell performance when the high intensity illumination is not uniform.

Previous works [24–26,33–44] have studied the solar cell electrical performance with non-uniform illumination intensity. Some authors have explored this issue through developing and validating models, finding generally a disproportionate loss of cell performance of several per cent [24–26,33–36]. Others use experimental methods [37–44], describing a loss in cell performance [38], an internal current and voltage drop [39], a loss in fill factor [44] and a mitigating effect in the spread of current density [42]. Several authors note that in point-focus CPV the irradiation profile resembles a gaussian distribution and therefore use such distributions in their works [28,37,42,44]. Others, like Ghitas and Sabry [40,41], focus on the location of shadows on the cell surface, specifically the edge as that is usually the area that receives the least amount of illumination.

In the current study the electrical parameters of III-V CPV solar cells under an extreme form of non-uniform illumination intensity are investigated experimentally by use of a homogeneous illumination source, with partially shaded cells using the shading factor S as introduced by Quaschning and Hanitsch [34]. Experiments under concentrated illumination are performed using a multiple-flash setup. The I-V characteristics of commonly applied InGaP/Ga(In)As/Ge triple shallow junction (TSJ) cells are investigated, as well as GaAs single junction cells, in-house grown to resemble the individual junction in a TSJ stack. In performance optimized TSJ solar cells for CPV the InGaP and Ga(In)As subcells are designed to be lattice matched for a certain spectral distribution of the incident light. However, as in practice the spectral distribution changes during the day, also the limiting subcell in power output optimized cells changes during the day [45]. In the red-shifted morning and evening spectrum the InGaP cell will be limiting while in the mid-day blue shifted spectrum the GaAs cell will be limiting. Also it is known that carrier recombination in the outer cell perimeter especially, is one of the major causes of performance losses in GaAs solar cells [46,47]. It may therefore be expected to also affect the electrical performance of CPV multijunction cells that contain a GaAs subcell, in particular because small CPV cells have a relatively larger perimeter to surface area ratio. On the other hand the relative contribution of this effect on output power diminishes when cells are operated at high light concentrations [48]. Therefore in the investigation of inhomogeneous cell illumination intensity carried out here, special attention is devoted to the outer cell perimeter. These recombination effects are usually determined by comparison of the dark diode characteristics of cells of varying surface area. However, the dark diode characteristic might not be representative for a solar cell under non-uniform illumination intensity. Especially in BICPV setup, where illumination intensity can be very high, and illumination non-uniformity can be severe. The nature of recombination losses in the perimeter are evaluated here, in illuminated conditions as is representative for solar cells operating in a CPV setup. The influence of the outer cell perimeter is determined by specifically illuminating this area, or excluding it from illumination while characterization of the overall cell performance is performed. The analysis is performed on the triple junction and single junction GaAs cells, and not on single junction InGaP or Ge, as they have been shown to not contribute significantly to these effects in MJ cells [46].

Finally a comparison is made between the partially shaded performance of typical single shallow-junction (SSJ), and single deep junction [49,50] (SDJ) GaAs solar cells, the latter of which have recently been shown by Bauhuis et al. [51] to display enhanced electrical performance under one sun illumination. GaAs cells with a device structure similar to the individual junctions in a CPV multi-junction cell have been grown with respectively a shallow and a deep junction and characterized under one sun, and concentration while partially shaded, in order to show the benefit of using a deep junction GaAs subcell in multijunction CPV cells.

2. Experimental

2.1. Device description

The CPV MJ solar cells under test are Spectrolab CDO100 C3MJ type CPV assemblies. These are 11.1 mm × 10.1 mm InGaP/Ga(In)As/Ge CPV solar cell assemblies, equipped with anti-reflection coating (ARC), and front contact metal tabs. The cells feature a silver front contact grid consisting of parallel, equidistant lines with a total surface coverage of 8.8%, and are optimized to achieve maximum performance under the ASTM G173-03 spectrum [52]. All subcells of this structure have a commonly applied thin emitter, thick base or in other words shallow junction geometry. Therefore in this study these cells will be referred to as Triple Shallow Junction (TSJ) cells.

Additionally, GaAs solar cells with shallow as well as deep junctions were studied. These were grown on substrate using MOCVD under conditions described in previous work [53]. For convenience these cells will be referred to as Single Shallow Junction (SSJ) and Single Deep Junction (SDJ) cells. Both cell types cells possess a 20 nm AlInP window and an AlGaAs back surface field. The emitter and base dopants are Si and Zn, respectively. The layer thicknesses and doping levels of the active layers of the investigated shallow and deep junction GaAs cells are summarized in Table 1.

The GaAs cell structures have been processed into test devices with an active area of 11.1 mm × 10.1 mm, and covered by a MgF2/ZnS ARC. Gold was applied for metallization on the front and back side. The front contact consists of parallel, equidistant grid lines of 4 μm thickness and a total surface coverage of 8.4%.

2.2. Electrical characterisation

One sun I-V characterization of the solar cells is performed using an ABET technologies Sun 2000 Class AAA solar simulator, which provides a uniform AM1.5G illumination over a 100 × 100 mm² area, with a maximum angular offset of 2°. The setup is equipped with a Keithley 2600 sourcemeter and data acquisition is performed using ReTa Tracer3 software. The solar cells are kept at 25° during measurement using a water cooled thermostat. The setup is calibrated using a calibrated reference cell before each measurement series. The same setup is used for determining dark diode characteristics of the cells. Shown datapoints are averages of four separate measuring series taken from different solar cells of the same.

I-V curves under concentrated light are obtained using a multiple-flash setup that applies a different fixed bias voltage across the cell during each flash. A broncolor pulso G Xe arc lamp having a maximum energy of 3200 J is used to apply highly concentrated light. The UV protection dome was replaced by a quartz dome to allow for higher UV-content. In this way the applied Xe spectrum better resembles the AM1.5 spectrum. A reflector is used to achieve high concentrations. The lamp is driven by a broncolor top as A4 source for a 6 ms flash. A KEPCO BOP 20-50MG source is used to bias the cell at a specified voltage during the flash. To measure the data a National Instruments

Table 1

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Emitter thickness (μm)</th>
<th>n-emitter doping (cm⁻³)</th>
<th>Base thickness (μm)</th>
<th>p-base doping (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs SSJ</td>
<td>0.15</td>
<td>2 × 10¹⁶</td>
<td>3.50</td>
<td>3 × 10¹⁶</td>
</tr>
<tr>
<td>GaAs SDJ</td>
<td>2.40</td>
<td>1 × 10¹⁷</td>
<td>0.10</td>
<td>1 × 10¹⁸</td>
</tr>
</tbody>
</table>
DAQ board is integrated into the system. The irradiance level is monitored using a reference cell having a linear response to the illumination level. In this manner, in fact I-V pairs for a continuous range of concentrations are obtained for the specified bias voltage during a single flash. I-V curves at any particular concentration are subsequently constructed from datasets obtained from multiple flashes conducted under different bias voltages. In this fashion, a possible shift of limiting subcell during a flash because of temporal spectral variations will not cause artificial discontinuities in the I-V curves, as the irradiance for any single I-V curve can be considered constant when using this multishaft method. Therefore, the limiting subcell is constant for each I-V curve. It should be noted however, that slight reductions in the GaAs subcell $FF$ might be masked when InGaP is current limiting and vice versa. No more than one flash is executed for every 30 s to prevent heating of the lamp, which could result in a red shift of the spectrum. The concentrations reported hereafter are determined by division of the measured, concentrated short-circuit current by the calibrated one-sun short-circuit current, and are therefore the effective concentrations rather than geometrical.

2.3. Shading

In order to achieve reliable data when the solar cells are partially shaded, good alignment between the solar cell and the shading material should be achieved. To do this, the specially developed probe station shown in Fig. 1 is used. It features a stage where the solar cell is loaded and kept in place by vacuum which simultaneously functions as the back contact probe, and a cover lid that serves as the front contact probe. Above the cell stage a mount is located that can be moved in the $x$ and $y$ directions very precisely. The mount can hold a 127 mm $\times$ 127 mm opaque shading screen that serves to apply partial shading to the solar cell. Various shading patterns are gained by the use of shading screens with differently shaped holes in. Using a microscope for inspection, precise alignment between the shading pattern and the solar cell is achieved. The microscope is removed before I-V characterization.

In this work two different shadow patterns are considered, which are illustrated in Fig. 2. We consider 'center shading', here represented by rectangular shading propagating from the middle of the cell towards the edges, as shown in Fig. 2a. In this way, the illuminated perimeter to illuminated area ratio $P_{ill}/A_{ill}$ increases more rapidly with the shading factor $S$ than in the rectangular case. Therefore this method is used to investigate the electrical performance at the perimeter of the cells compared to the bulk cell area. As an inverse of the previous, 'edge shading' is applied as shown in Fig. 2b.

These methods are applied to the commercial TSJ CPV cells as well as the in house grown single junction cells discussed in Section 2.1, under both 1 sun and concentrated illumination. The measurements on the single junction cells will be used to gain a more precise understanding on the TSJ cell electrical performance. Additionally the performance of the shallow junction cells are compared to that of their deep junction counterparts.

When cells of different types need to be compared, in order to be able to make good comparisons, the electrical parameters of the solar cells are normalized via:

$$X_S(S) = \frac{X(S)}{X(S = 0)},$$

where $X(S)$ is a cell parameter for a given $S$. 

Fig. 1. The probestation used for application and alignment of the shading on the solar cells with (a) showing the interior; and (b) a plate is inserted in the mount and can be precisely move into position by the turning spindles. A microscope is used to ascertain exact alignment of the shading plate with the solar cell and microscope equipped. The numbered components are (1) cell stage with brass back contact; (2) vacuum to ensure good back contacting; (3) front contact point; (4) clamp to hold the cell in place, simultaneously contacting front contact tabs; (5) moveable mount for shading plates; (6) microscope for checking alignment between shading plate and solar cell; and (7) spindles for moving the shading plate mount.

Fig. 2. The applied shading patterns; (a) 'center shading'; and (b) 'edge shading'. For center shading an increasing shading factor $S$ causes a larger illuminated perimeter-to-area ratio.
3. Results

3.1. Shaded performance under one sun illumination

When center shading (Fig. 2a) is applied, $P_{in} / A_{ill}$ increases rapidly with $S$. Conversely, when edge shading (Fig. 2b) is applied the outer cell perimeter is directly excluded from the overall cell performance. Therefore comparison of the cell electrical parameters under both conditions yields information on nonidentical performance of the center cell area as compared to the outer perimeter. The I-V characteristics of the triple junction cells, as well as SSJ and SDJ GaAs cells, for both center and edge shading have been determined for increasing shaded fraction $S$ ranging from 0 to 0.95. Fig. 3 shows normalized electrical parameters of the solar cells under these conditions. The $I_{SC}$ (Fig. 3a) shows, for all three cell types, for both center and edge shading, a proportional decrease as a function of $S$, explained by the diminished overall illumination, via:

$$I_{SC}(S) = (1 - S) I_{SC}(S = 0).$$

Besides $I_{SC}$ also $V_{OC}$ and $FF$ of the cells decrease with $S$ but only to a limited extent. Also, when considering $V_{OC}$ (Fig. 3b) differences between the cell types become apparent. The decrease in $V_{OC}$ is much less severe

![Graph showing normalized electrical parameters of triple shallow junction cells (circles), as well as single shallow junction (triangles) and single deep junction (squares) GaAs cells, under one sun illumination, as a function of edge shading (brighter hues) and center shading (darker hues). The data points are averages of four separate measuring series taken from different solar cells of the same type, with (a) short-circuit current; (b) open circuit voltage; and (c) fill factor.](image1.png)

Fig. 3. Normalized electrical parameters of triple shallow junction cells (circles), as well as single shallow junction (triangles) and single deep junction (squares) GaAs cells, under one sun illumination, as a function of edge shading (brighter hues) and center shading (darker hues). The data points are averages of four separate measuring series taken from different solar cells of the same type, with (a) short-circuit current; (b) open circuit voltage; and (c) fill factor. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

![Graph showing experimental open circuit voltage as a function of shading of the SSJ and SDJ GaAs cells on log scale, compared to the theoretical values determined from the dark curves (shown as continuous lines). The dashed lines are linear fits for $S$ ranging from 0 to 0.7, representing the standard linear decline of $V_{OC}$ with $ln(l_{SC}/l_0)$ for decreasing irradiance.](image2.png)

Fig. 4. Experimental open circuit voltage as a function of shading of the SSJ and SDJ GaAs cells on log scale, compared to the theoretical values determined from the dark curves (shown as continuous lines). The dashed lines are linear fits for $S$ ranging from 0 to 0.7, representing the standard linear decline of $V_{OC}$ with $ln(l_{SC}/l_0)$ for decreasing irradiance.
for the SDJ GaAs cells (green square markers) amounting to 9.5% relative decrease at \( S = 0.95 \), compared to 11.6% relative decrease for SSJ GaAs cells (yellow and red triangular markers) and 13.8% relative decrease for triple junction cells (blue circular markers). Within any single cell type however, no significant difference in electrical parameters is observed between center or edge shading. The observed \( V_{OC} \) decrease for increasing \( S \) can be only in part attributed to the lower irradiance for increasing \( S \), as shown in Fig. 4. Here, \( V_{OC} \) for all cells is shown as a function of \( S \) on a logarithmic scale. \( V_{OC} \) exhibits a \( \ln \) dependence on \( I_{SC} \) and therefore on \( S \), shown here by the dashed linear trend lines. For lower \( S \) values, the \( V_{OC} \) decreases according to theory. However at high shading factors of \( S > 0.7 \), a disproportionate loss in \( V_{OC} \) of a few percent arises. Also from the \( FF \) (Fig. 3c), the difference between the cell types is readily apparent. In this case the larger decrease of the SSJ GaAs \( FF \) for increasing \( S \) stands out, caused by its higher series resistance in comparison to the other cell types. Conversely, the SDJ GaAs and triple junction \( FF \) are much more constant for increasing \( S \), only showing a decrease of a few percent relative even when \( S \) approaches 1. Again, center and edge shading yield the same results within any single cell type.

The results show that the overall cell performance under illumination is independent of the location of illumination, in spite of perimeter recombination effects. We suggest this occurs because the influence of perimeter recombination is equal in the edge – and center shaded cases because the generated current spreads out throughout the entire cell volume via lateral diffusion effects, so the perimeter recombination affects cell performance regardless of the location of illumination. In order to evaluate this, effects caused by the perimeter recombination at high \( S \) are next studied in more detail. The dark curves of the SSJ and SDJ GaAs cells are considered here, and shown in Fig. 5. The dark recombination current is described by:

\[
I_{rec} = I_0 \left( \exp \left[ \frac{qV}{nkT} \right] - 1 \right) + I_0 \left( \exp \left[ \frac{qV}{2nkT} \right] - 1 \right).
\]

(3)

with \( n = 1 \) the radiative, and \( n = 2 \) non-radiative recombination. The non-radiative recombination mainly stems from the depletion zone and the perimeter. For large cells (\( \geq 1 \text{ cm}^2 \)), the perimeter recombination has a strong influence at voltages up to 1.1 V [46] in the shallow junction case. For deep junction cells, at one sun conditions, at operating voltage, the contribution of non-radiative recombination is lower [51]. The ratio between the recombination currents is voltage dependent; at low voltages non-radiative recombination effects are relatively stronger and vice versa. At constant voltage, for instance \( V_{OC} \), the following holds:

\[
I_{rec} = I_0 \left( \exp \left[ \frac{qV_{OC}}{nkT} \right] - 1 \right), \quad \text{with} \quad 1 \leq n \leq 2.
\]

(4)

If the shape of the I-V curve is assumed not to change with increasing irradiance, the total current becomes:

\[
I = I_{rec} - I_{OC}.
\]

(5)

At \( V_{OC} \) conditions \( I \equiv 0 \) and \( I_{rec} = I_{OC} \) so that for \( I_{rec} \gg I_0 \):

\[
V_{OC} = \frac{nkT}{q} \ln \left( \frac{I_{OC}}{I_0} \right).
\]

(6)

Hence the dark curve provides combinations of \( I_{OC} \) and \( V_{OC} \). Substitution of Eq. (2) in Eq. (6) yields an expression for \( V_{OC} \) that accounts for cell shading:

\[
V_{OC}(S) = n(S) \frac{kT}{q} \ln \left( \frac{1 - S}{I_{OC}(S = 0)} \right).
\]

(7)

with \( n \) and \( I_0 \) not constant as a function of \( S \). In order to determine the \( n \) and \( I_0 \) at different shading values, illuminated \( I_{SC} \) values for different shading have been superimposed on the dark curves (Fig. 5) yielding the corresponding \( V_{OC} \) values. Because the shape of the curve is assumed to be unaffected by irradiance, the dark curve directly yields corresponding \( V_{OC} \) values, and \( n \) and \( I_0 \) are determined from the slope of the curve. The latter are shown in Fig. 6. The dark curves show clearly a lower \( n \) and \( I_0 \) for the SDJ design, which is a correlated to the n-type absorbers lower diffusion factor as explained in [49]. The difference in absorber doping level between the SDJ and the SSJ design can not account for this difference. Therefore an n-type absorber, in terms of

Fig. 5. Dark diode characteristics of the SSJ and SDJ GaAs cells.

Fig. 6. Cell parameters of SSJ and SDJ GaAs cells as a function of shading as determined from the dark curves, showing (a) recombination current; and (b) ideality factor.
low $I_0$ will show a better performance over a large range of doping levels [49,50]. Because of this, the SDJ design with its relatively thicker n-type absorber outperforms the SSJ design. Therefore, especially in thin cells, the SDJ design is preferred. Clearly, $n$ and $I_0$ both increase strongly at high $S$ values. This occurs because the ratio of radiative and non-radiative recombination shifts towards non-radiative ($n = 2$) at low irradiance. This explains the deviation from standard decrease of $V_{OC}$ with $S$, described in Fig. 4. The $V_{OC}$ values determined by the method described above constitute a theoretical decline of $V_{OC}$ with increasing $S$, which takes the increasing $n$ and $I_0$ into account. These values are compared to the experimentally determined $V_{OC}$ in Fig. 4. An excellent overlap between curves determined from illuminated I-V measurements and dark curve measurements is shown, for both the SSJ and SDJ cells. Additionally, both center and edge shaded experimental data agree very well with the theoretically determined $V_{OC}$. Therefore it is clear that specifically including or excluding the outer cell perimeter from being illuminated does not alter the degree in which perimeter recombination effects the cell performance. Hence the lateral current spreading effect as suggested above must be responsible for bringing carriers close to the outer perimeter where they recombine, even when no carriers are generated at those locations.

Summarizing, aside from a strongly diminished FF for SSJ GaAs cells, the performance of the solar cells is quite robust in partially shaded conditions. For very high shading factors, a slightly diminished cell performance has been observed. This heavily shaded scenario – that results in only a minor effect – is of course a gross overstatement of the inhomogeneities in irradiance encountered in application. Therefore, the total illumination intensity of the cells can be considered to be the determining factor for the cell performance, and also for the magnitude of perimeter recombination effects, rather than the homogeneity of illumination intensity. Because of this, small inhomogeneities are not expected to cause severe detrimental effects on the cell performance in application.

### 3.2. Shaded performance under concentrated illumination

Concentrated light I-V characteristics have been determined for all three cell types using the multiple flash setup as described in Section 2.2. Using this setup, characteristics for a continuous range of concentrations are determined at once. However, for the sake of brevity and clarity, only two concentrations will be shown. For the TSJ cells, these are $C = 500$ and $C = 1000$, while for the GaAs cells, $C = 250$ and $C = 500$ are shown. These ranges are chosen because of current constraints of the equipment. The concentrations for the GaAs cells are lower than for the TSJ, because the GaAs cells produce roughly double the current of the TSJ for equal irradiance. Again, center and edge shading is applied to the solar cells with $S$ ranging from 0 to 0.95. Fig. 7 shows normalized electrical parameters of the solar cells under these conditions. Here, the normalization holds the additional benefit of allowing comparison of measurements performed at different concentrations.
For all three cell types, for both center and edge shading, on all concentrations, \( ISC \) exhibits a linear decrease as a function of \( S \), as shown in Fig. 7a. The relative decrease in \( V_{OC} \) for concentrated illumination, shown in Fig. 7b, is much less than for one sun illumination. This occurs because \( V_{OC} \) and also \( I_0 \) are higher in this scenario. Therefore \( n \) approaches 1 and \( I_0 \) is virtually constant for increasing \( S \). Additionally, the differences between the different cell types are far less pronounced. Again, differences in performance when the cells are edge shaded (lighter colours) or center shaded (darker colours) remain absent. The trends in the FF (Fig. 7c) are vastly different for all cell types than at one sun illumination. This occurs mainly because the cells operate with a certain optimum concentration as will be further elaborated in Section 3.3. First note that for all cell types, again no significant differences are found that can be linked to the location of illumination (edge vs center). For the TSJ cells, the FF is quite constant as a function of \( S \), with the average FF being somewhat higher for \( C = 1000 \) (open markers), compared to \( C = 500 \) (full markers). This may occur because the optimum concentration for these cells lies around \( C = 800 \), thus for \( S = 0 \), which is the normalization point, the cell operates closer to its optimum during the \( C = 1000 \) measurement series. It should be noted however, that these differences in FF are only marginal (within 2% from 1) and therefore could be considered to be within the measurement error. For both SSJ and SDJ GaAs cells, for \( C = 250 \) (full markers) the FF shows some deviations as a function of \( S \). Again, the changes are very minor so the FF may be considered constant as a function of \( S \) in these cases. The effect is much more pronounced in the \( C = 500 \) (open markers) measurements, as for \( S = 0 \) the cells operate further away from their optimum concentration in this scenario.

It is apparent that the partially shaded cell performance is predominantly determined by the total irradiance, rather than the location or homogeneity of illumination intensity under concentration as well as one sun illumination. The lesser decrease of \( V_{OC} \) with increasing \( S \) under concentrated light supports this. Also, the increasing FF with \( S \) for the GaAs cells point in the same direction, which becomes clear when total irradiance received by the shaded cell is considered via:

\[
E_0(S) = E(S = 0) \cdot (C \cdot S), \tag{8}
\]

so that the combination of \( C = 250 \) and \( S = 0.5 \) is assumed to be equivalent to \( C = 125 \). In this assumption, for a constant \( C \) that is above the optimum concentration, increasing \( S \) can be considered similar to decreasing \( C \), thus getting closer to the optimum concentration. This agrees with the trends shown in Fig. 7c, and reinforces the suggestion that the generated current spreads out from the illuminated area to fill the entire cell volume. Also under concentration, no significant differences in cell performance have been found for illumination of the outer cell perimeter or the cell center. Therefore, lateral spreading of the current density can be considered to bring perimeter recombination effects into play regardless of the location of illumination on the cell surface. Additionally it may be noted that under concentration, the individual subcells in a MJ stack operate at higher voltages dependent on the concentration. At higher voltages recombination is dominated by the quasi-neutral regions, so the impact of the perimeter recombination
is relatively lessened. Again, a significant loss of cell performance is only observed at very high shading factors. Because of this, small inhomogeneities in illumination intensity across the cell surface are not expected to cause detrimental effects on the cell performance in CPV systems.

3.3. Enhanced performance of deep junction GaAs cell under concentration

In the previous two sections, the electrical parameters of SSJ and SDJ GaAs cells were shown to follow virtually the same trends for increasing shaded fraction $S$ for both one sun and concentrated illumination. However, it is important to note that while the cells exhibit a similar dependency on inhomogeneities in the illuminated profile, the actual electrical cell parameters as shown in Fig. 8, are not equal for the SSJ and SDJ cells. Fig. 8a shows that for both cell types $I_{SC}$ drops proportionally to $E_i$ with increasing $S$ as described above. Moreover the figure shows that there is very little difference in current production between the SSJ and SDJ cells. Fig. 8b on the other hand shows that under concentrated light, the SDJ cell always generates an increased voltage of over 43 mV compared to its SSJ counterpart. As the generated voltage is a very important parameter in concentrator solar cells, this increase can be a major benefit in CPV cells. Similarly, Fig. 8c shows the increased $FF$ for the SDJ cells compared to the SSJ to be up to 2%. An interesting feature is that the $FF$ of both cell types remain fairly constant with increasing $S$ for the $C = 250$ series, while they exhibit a significant increase in the $C = 500$ series. This occurs because the cells have an optimum operating concentration, which is represented by the maxima of the curves shown in Fig. 9. In this figure, the $V_{OC}$ (a), $FF$ (b), and efficiency (c) of deep and shallow junction GaAs cells are compared as a function of light concentration. The effective concentration of each data point in Fig. 8c can be obtained by multiplication of the applied concentration for the series ($C = 250$ or $C = 500$) with the particular $S$ value. The $C = 250$ series in Fig. 8c exhibits a fairly constant $FF$ with increasing $S$, because the effective concentration ranges from 250 to 10, i.e. providing $FF$ values relatively close to the maximum in Fig. 9b. For the $C = 500$ series on the other hand the low $S$ values represent an effective concentration exceeding 250, i.e. well beyond the optimal concentration where the $FF$ values decrease rapidly (see Fig. 9b). Fig. 9 further shows clearly that for the entire range of investigated concentrations, the SDJ cell exhibits an increased $V_{OC}$ and $\eta$ compared to the SSJ cell. For concentrations exceeding 10X, the SDJ cell also exhibits a higher $FF$ than the SSJ cell. The increased performance of the SDJ design over the SSJ was shown to persist under inhomogeneous illumination intensity in Sections 3.1 and Sections 3.2. Therefore use of this SDJ design for the GaAs subcell in CPV multi-junction solar cells may provide an interesting route towards cells with further enhanced performance.

4. Conclusions

The electrical parameters of CPV solar cells under an extreme form of inhomogeneous illumination intensity profiles have been studied in detail. Local shading has been applied as a measure for inhomogeneity rather than variations in illumination intensity. This is done because shading represents the most extreme case of inhomogeneous intensity, so that possible effects on cell performance will be revealed most strongly. Commercially available InGaP/Ga(In)As/Ge cells, as well as shallow and deep junction GaAs cells resembling the GaAs subcell in the
TSJ cells, have been I-V characterized when partially shaded. It has been shown that the electrical performance of the solar cells under partial shading is quite robust. A performance loss in the order of 4% has been observed for very high S. Such heavy shading grossly overstates the inhomogeneities in irradiance encountered in application. Hence, an inhomogeneous cell illumination intensity profile as commonly found in CPV systems, can be considered to have no influence on the overall electrical cell performance.

More importantly, the location of the shading on the solar cell area is also found to be of no consequence for the cell performance for the investigated conditions. In experiments where the outer perimeter of the cells are specifically illuminated, or excluded from illumination, the cell performance as a function of S is equal for all cell types. Lateral spreading of the current density likely causes perimeter recombination effects to affect the cell performance regardless of the location of illumination. These perimeter recombination effects will therefore not have a further detrimental effect on the cell performance when the illumination intensity profile is not homogeneous. However, a reduction of these perimeter recombination effects altogether will be beneficial to the cell performance.

These findings show clearly that even partial shading in the cell illumination pattern caused by elaborate optical systems, such as the ones often applied in BICPV, do not inhibit the electrical performance of the solar cells strongly. Accordingly, an inhomogeneous illumination intensity profile may also be considered to have little impact on the cell performance. As a consequence, a large degree of design freedom exists for the optical systems. This offers many opportunities for the development of building integrated concentrator photovoltaics that meet all the design challenges of the built environment.

Additionally, shallow junction GaAs solar cells have been developed that resemble the GaAs subcell in a TSJ cell structurally, as well as a deep junction counterpart. The cells have been equipped with an ARC and front contact grid resembling that of the TSJ cells. The normalized electrical parameters of these cells exhibit similar trends when partial shading is applied. Therefore SDJ and SSJ cells can be considered to function equally well under inhomogeneous illumination intensity profiles. However, the SDJ cells have been shown to exhibit a significantly increased V_OC (40 mV), FF (2% absolute), and efficiency (2% absolute) under a wide range of concentrations compared to the SSJ cells. Therefore use of this SDJ design for the GaAs subcell in CPV multi-junction solar cells may provide an interesting route towards cells with further enhanced performance.

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References

[36] P. Sharma, M. Wilkins, H. Schiermier, K. Hinzer, Modeling nonuniform irradiance and chromatic aberration effects in a four junction solar cell using spice, in:


