Integrated series/parallel connection for photovoltaic laser power converters with optimized current matching

Lukas Wagner | Sebastian Kasimir Reichmuth | Simon P. Philipps | Eduard Oliva | Andreas W. Bett | Henning Helmers

Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, 79110, Germany

Correspondence
Henning Helmers, Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstrasse 2, Freiburg 79110, Germany.
Email: henning.helmers@ise.fraunhofer.de

Abstract
In this paper, we present a stepped architecture optimized for current matching in high-voltage laser power converter photovoltaic (PV) cells. The integrated series/parallel connection in stepped PV cells combines the advantages of well-known multijunction and multisegment approaches with respect to current matching, whereas their specific drawbacks are circumvented. The superior misalignment tolerance of stepped PV cells in comparison with multisegment cells is shown by simulations of the maximum acceptable misalignment (MAM) for a range of devices with various output voltages. We present the first realization of stepped PV cells with two stacked GaAs-based pn-junctions. Thereby, the unique properties of the lateral current flow in the bottom cell and the assessment of the optical absorption in the sub-cells are discussed. Moreover, the effects of segmentation and number of stacked junctions on the I-V characteristics are investigated. Finally, the behavior towards misalignment of a laser spot is studied for stepped and multisegment PV cells. An optimal current matching for misalignment-prone power-by-light systems is found with a six-segment stepped PV cell.

KEYWORDS
integrated series connection, mismatch losses, multijunction, power-by-light, power-over-fiber, stepped architecture, vertical-lateral integration

1 | INTRODUCTION

Photovoltaic (PV) laser power converters transform monochromatic (laser) light into electrical power. They are key components in power-by-light systems for optical power transmission. Such systems are used to power electric devices like sensors in environments where electricity supply via current-carrying cables is not desirable.

With a band gap energy of 1.42 eV, GaAs-based PV cells are well suited for efficient conversion of laser light in the 808- to 850-nm range. GaAs grown by metal organic vapor phase epitaxy (MOVPE) can be fabricated in very high material quality, and consequently various research groups have published devices with monochromatic light to electricity conversion efficiency above 55%.1-12

In the radiative limit (external quantum efficiency [EQE] of unity for photon energies above or equal the band gap energy, zero losses because of thermalization, i.e., band gap energy equals photon energy, no shading, no resistive losses, and perfect material with radiative recombination only and an ideal back mirror), the theoretical efficiency potential for PV laser power converters lies beyond 80%.13

[Correction added on 28 January 2021 after first online publication: Affiliation and corresponding author has been updated in this version.]
The output voltage of the PV cell is determined by the PV material and is around 1 V for GaAs. Yet, to power electric circuits, often higher voltages (e.g., 3.3 or 5 V) are desired. A well-known way to increase the output voltage of a PV cell is the division of the cell into several subcells that are connected in series. Thereby, the subcell voltages add up, whereas the current is divided among the subcells. This division of current also reduces resistive losses that scale quadratically with the current, which is especially important in high-power applications.

For such integrated series connection in PV laser power converters, two architectures are state-of-the-art: the “multijunction” approach where several subcells are stacked by vertical interconnection and the “multisegment” approach where series connection is achieved by lateral segmentation (also known as monolithic interconnected modules, MIMs). For efficient operation, the currents in the subcells need to be well matched. Unfortunately, in practice, both architectures suffer from intrinsic nonideal current matching.

In multijunction cells, the absorption of light and thus generation of photocurrent in the subcells generally follow Beer–Lambert’s law of exponential absorption. Accordingly, the thicknesses of the individual subcells need to be adjusted to achieve current matching. Because of the temperature dependence of the cell’s absorption coefficient, accurate current matching in multijunction cells can only be achieved for a specific operating temperature.

In multisegment cells, this layer thickness-dependent current mismatch is avoided. Here, the currents of the subcells are defined by the illuminated segment areas. As a consequence, a misalignment of the laser light spot on the PV cell leads to current mismatch and, thus, a drop in efficiency. As will be elaborated below, this causes significantly severer losses than the pure spillage of light outside the active PV cell area, which represents a fundamental loss mechanism in all device architectures.

In this work, we introduce a PV cell architecture with improved misalignment tolerance based on an integrated serial/parallel connection of subcells in a combined lateral/vertical segmentation. With this so-called stepped architecture, the advantages in current matching of both multijunction and multisegment architectures are combined, whereas their specific drawbacks are circumvented. We compare calculations of the misalignment tolerance for the three architectures. Finally, practical realizations of a range of design variations of stepped PV cells are presented and discussed.
PV cell architectures, as listed in Table 1. Low sensitivity against temperature and layer thickness variation is achieved by current matching via the segment areas, whereas the combined series/parallel connection yields high misalignment tolerances. In the next section, this qualitative finding is examined further by a quantitative assessment of the misalignment tolerance.

Table 1 summarizes also technological constraints of the architectures. The technological effort to process stepped PV cell depends on the number of junctions \( j \), which is in turn proportional to the desired output voltage. For 2-V GaAs-based applications, the number of processing steps for stepped cells is higher than for multijunction cells and lower than for multisegment cells. The absorber thickness of the crystal layers for stepped PV cells increases linearly with the number of junctions \( j \), whereas for multijunction devices, the thickness increases by a much lower extent, remaining in the range of that of a single junction PV cell. To give an example, for 3-V GaAs devices under 810-nm illumination, the required absorber thickness is 3.7 \( \mu \text{m} \) for a multijunction, 4.7 \( \mu \text{m} \) for a multijunction, and 11.1 \( \mu \text{m} \) for a stepped PV cell for an absorptance of 0.98. Additional LCLs and tunnel diodes further increase the epitaxial effort. The need for thick epitaxy structures may pose an economic obstacle for the fabrication of high-voltage stepped devices with many stacked, fully absorbing junctions. Regarding the area loss because of segmentation, stepped cells are only affected by nonideal steepness of the segment flanks. It is therefore significantly lower compared with multisegment cells, where the segments are separated by isolation trenches.\(^{14}\)

3 | SIMULATED MISALIGNMENT TOLERANCE

The following assessment of the misalignment tolerance is based on the model introduced in Wagner et al.\(^{19}\) We consider a circular symmetry for PV cell and light spot, which is the typical geometry for optical fiber-based systems. The misalignment dependence of the cell current is computed by the spatial convolution of the irradiance profile and the subcells’ spatial responsivity. For simplicity, the responsivities are assumed constant over the area of the subcell, and
the irradiance is simplified to a constant flat-top profile. There are two characteristic axes for a displacement of the light spot that we call the “best case” and the “worst case” axis, as depicted in Figure 2A. In the worst case (Axis 1), the light spot is displaced along the center of one segment, which will lead to the highest power loss, whereas in the best case (Axis 2), it is displaced along the edge of two segments edge, yielding the lowest power loss.

Figure 3 illustrates the behavior of current limitation for a two-junction, four-segment stepped PV cell with an electrical interconnection as depicted in Figure 2C. Figure 3 shows simulations of the normalized photocurrents in each subcell as a function of a displacement of the light spot along the “worst case” axis. The plot shows that for small displacements, the current is limited by Subcell 1, which comprises of the poorly illuminated Segment 1 and the fully illuminated Segment 3. The superior misalignment tolerance of the stepped geometry is most evident at an extreme displacement of one cell radius, where the current in the multisegment cell, which is currently limited in Segment 1, is zero, whereas in the stepped PV cell, Subcell 1 still provides 50% of the initial current.

The thin black line depicts the reference case of current loss because of misalignment for one segment \( n = 1 \) as in a multijunction cell. It is noteworthy that as a result of symmetry for a displacement along the “best case” axis, the combined serial/parallel geometry always behaves as this ideal \( (n = 1) \) case: since then, the photocurrents of both subcells are equally affected from spillage.

A quantitative comparison of the different architectures can be assessed by the maximum acceptable misalignment, \( \text{MAM}_{90} \), for which 90% of the maximum photocurrent (i.e., the current at optimal alignment) can be ensured. This critical displacement is illustrated by a horizontal arrow in Figure 3.

Figure 4 shows the \( \text{MAM}_{90} \) for a different multi-segment and stepped PV cells as a function of the number of segments. We distinguish displacements along the best (grey diamonds) and worst case axis (black squares). The ordinate shows the \( \text{MAM}_{90} \) as acceptable displacement in percent of one cell radius. The optimal case of an \( n = 1 \) segment cell is marked by an upper horizontal black line and, thus, represents the case of nonsegmented single-junction or multijunction cells.

Figure 4A shows that in multijunction PV cells, for both axes, the \( \text{MAM}_{90} \) drops with increasing segment numbers and converges to a lower limit of 5.13% of the cell radius, as marked by the lower horizontal line.

Figure 4B shows a converse trend for the stepped geometry. As noted above, for displacements along the best case axis, the curve of the stepped PV cell lies on the \( n = 1 \) upper value. For the worst case axis, the \( n = 2 \) case for stepped design agrees with the multijunction cell. With increasing segment numbers; however, the \( \text{MAM}_{90} \) rapidly increases for the stepped design and converges to the upper limit of 15.72% of the cell radius. In other words, the \( n = 1 \) case is equivalent to an infinite number of segments \( n \rightarrow \infty \) in the stepped architecture. Here, the stepped design yields a three times larger misalignment tolerance than the multijunction architecture. Yet, as area losses as well as perimeter recombination losses increase with increasing...
segmentation, extremely high segment numbers have no practical relevance. Another remarkable feature of the plot in Figure 4B is the discontinuities in the worst case behavior. These are due to a toggling between top and bottom cell as limiting subcell for different segment numbers.

Yet one has to keep in mind that Figure 4B only considers two-junction stepped PV cell, that is, GaAs cells with about 2-V output voltage, whereas for the multisegment case in Figure 4A, the voltage increases proportionally with the number of segments. In the 2-V case, compared with multisegment cells, the stepped geometry has a two times higher misalignment tolerance for high segment numbers ($n \rightarrow \infty$). For an $n = 6$ segment cell, already 94.4% of this limit is reached.

Figure 4c,d compares the misalignment along the worst-case axis for stepped PV cells with a higher number of junctions $j = 3$ and 4 and, thus, higher output voltages of about 3 and 4 V for GaAs absorbers, respectively. As for the 2-V case, in the stepped architecture, the MAM$_{90}$ converges to the $n = 1$ multijunction case with increasing segment numbers. In the three-junction device, this upper limit is approached by 97.6% for an $n = 9$ segment cell. For a four-junction stepped PV cell, the MAM$_{90}$ rises slower; 90.9% of the upper limit is reached for $n = 12$ segments and 96.7% for $n = 20$ segments.

4 | EXPERIMENTAL REALIZATION

For the first realization of stepped PV cells, a range of two-junction cells with various segment numbers were fabricated. The crystal layers (compare Figure 1A) were grown by MOVPE on a GaAs substrate with an Aixtron G4 planetary reactor. The nominal thickness of the $pn$-junction was 3.65 μm. The processing of circular PV cell with 1.039 mm radius composed of four photolithography steps: First, the top cell was partly removed by selective wet etching. Afterwards, a

![Figure 5](image-url)
Ta$_2$O$_5$/MgF$_2$ antireflective coating optimized for 810 nm was evaporated as well as a Pd/Ge-based front contact grid metallization with an Ag finish. The cells on the wafer were separated among each other by a mesa etch step.

In the following, we highlight the current flow and the optical absorption as unique features of the stepped architecture and discuss the effect of the number of segments and junctions on I-V characteristics.

### 4.1 Lateral current flow

Figure 5A shows the path of the electric current in the top and bottom subcell of a two-junction stepped device. In the upper subcell, the current is transported radially to the outer wiring as in common PV cells. Fundamentally different is the current flow in the bottom subcell, which flows in azimuthal direction into the LCL between the two subcells.

For the experimental realization, a novel front contact grid was designed for the bottom cell. The layout was calculated such that both shadowing and resistive losses are minimized, based on a model following Joule’s law similar to the model for radially contacted multisegment cells presented by Pena and Algora. The grid consists of azimuthal metal fingers that collect current flowing in radial direction and carry it to radial bus bars at the segment edge. The bus bars help to equally inject the currents back into the LCL from where they flow under the top cell. The algorithm for the computation of the bottom grid is documented in the Appendix.

Figure 5B displays a scanning electron microscopy (SEM) image for a top view on a six-segment cell. The different grid structures in azimuthal and radial direction mark the bottom and top cell segments, respectively. The current on the top cell grid is finally collected by the large metal contact area surrounding the cell.

### 4.2 Optical absorption in top and bottom cell

To obtain high efficiencies in stepped PV cells, the subcells need to be sufficiently thick that practically all light is absorbed. Because of the series connection with the bottom cell, the absorption in the top cell cannot be directly measured, and two approaches have been followed to access the top cell current. In a first approach, unstructured two-junction ($j = 2, n = 1$) cells were processed. Because of shadowed bottom cell connected in series with the fully absorbing top cell, a device current close to zero would be expected in the first place. Yet, in contrast, we found a remarkably high current which we could attribute to luminescence coupling between the two junctions, as further discussed in Walker et al.

In a second approach, two test structures were fabricated for which the EQE was measured with a diffraction grating monochromator. The EQE of the bottom cell could be easily accessed with a test structure from which the top cell was completely removed. To access the top cell current, segmented structures were processed with a mismatch of the areas such that the bottom cell current was much larger than the top cell current. The area mismatch was determined with an optical microscope to 0.52:1. Therefore, the limiting current of the top cell determined the current of the overall cell.

Figure 6 shows the corresponding EQE of the single bottom cell (black line) and the top-limited cell (grey dashed line). The EQE of the latter was multiplied by the corresponding scaling factor to account for the lower active area. The curves match up remarkably well, especially above 700 nm, that is, in the spectrum where the PV cell is operated. Optical simulations (transfer-matrix method), and complementary sheet resistance measurements indicate that the discrepancies for wavelengths below 700 nm are attributed to minor deviations in the different LCL layers. We conclude that this method seems to be valid to access the top cell EQE of a two-junction cell. It shows that in our devices, at the target wavelength of 809 nm, practically all light is absorbed in one subcell layer.

### 4.3 Effect of segmentation and number of junctions

Figure 7A shows the characteristic light I-V parameters of 10 samples each of stepped PV cells with 2, 4, 6, 8, and 12 segments, measured with an automated flash-based setup under broad band illumination on a temperature controlled chuck at $T = 25$ °C. Statistical information of the data is represented in a box–whisker plot (left); the measurement result is displayed right of each box. The upper and lower box boundaries mark the 25 and 75 percentile with the horizontal band inside the box representing the median. The whiskers enclose data points within the 1.5 interquartile range. For better comparison of the effect of segmentation, these samples feature no front metallization to rule out effects of different grid designs. The plot shows that the influence of segmentation on $V_{oc}$ is negligible. Also, for the $I_{sc}$, no clear trend is observed. The maximum output power $P_{mpp}$ is most strongly influenced by the fill factor (FF), which is low for the $n = 2$ segments.
case and then increasing with \( n = 4 \) and 6. For larger segment numbers, the FF decreases again. For the low-segment case \( (n = 2, 4, \text{ and } 6) \), the dominant factor influencing the FF is the distributed series resistance contributions from lateral conduction in the window layers of both top and bottom subcell. For \( n = 2 \), the currents generated in the bottom cell have the longest average distance to the top cell. With increasing segment numbers, this path becomes more and more similar. For large segment numbers \( (n = 8 \text{ and } 12) \), the increased perimeter because of more etch flanks may cause significantly increased perimeter recombination loss. Considering that the misalignment tolerance increases with segmentation, this indicates that a six-segment stepped PV device is a good candidate for high-efficient power-by-light systems.

Thus, we studied the influence of a six-segment device with an optimized front grid under various 809-nm laser illumination intensities.\(^\text{22}\) Figure 7B compares the \( V_{oc} \) versus laser illumination intensity measurement of a six-segment, two-junction stepped PV cell with a single-junction (bottom cell only) device. For better comparison, the \( V_{oc} \) is divided by the number of junction \( j \). Essentially, both curves follow the slope corresponding to a diode ideality factor \( n_{ID} \) of one (blue line). At lower light intensities, the \( V_{oc} \) in the stepped device is lower than in the single-junction cell, which can be explained by additional perimeter recombination at the flanks of the top subcell segments that saturates at higher intensities. At high intensities, the open-circuit voltage drops slightly compared with the expected \( n_{ID} = 1 \) shape which is attributed to heating of the PV cell during the measurement. When comparing the maximum output power of the two-junction stepped cell with the single-junction device under similar laser power, a power-independent ratio of about 94% has been observed; in other words, the stepped architecture causes a loss of about 6%\text{rel} compared with a conventional single-junction cell.
Figure 8 shows the measured normalized photocurrent of a six-segment stepped and a multisegment PV cell (similar to the one investigated in Kimovec et al.\(^{20}\)) against the displacement of the light spot along the best and worst case axes. The cells were illuminated by a homogenized 809-nm laser light spot that was shaped by two vertically stacked circular optical apertures of the radius of a cell to approximate a top-hat profile. The light profile does not exactly resemble a sharp top-hat profile which excludes a quantitative comparison with the \(\text{MAM}_90\) value discussed above. However, the superior misalignment tolerance of the stepped design becomes apparent.

4.4 | Misalignment tolerance under a laser spot

Figure 8 shows the measured normalized photocurrent of a six-segment stepped and a multisegment PV cell (similar to the one investigated in Kimovec et al.\(^{20}\)) against the displacement of the light spot along the best and worst case axes. The cells were illuminated by a homogenized 809-nm laser light spot that was shaped by two vertically stacked circular optical apertures of the radius of a cell to approximate a top-hat profile. The light profile does not exactly resemble a sharp top-hat profile which excludes a quantitative comparison with the \(\text{MAM}_90\) value discussed above. However, the superior misalignment tolerance of the stepped design becomes apparent.

5 | CONCLUSION

In this paper, we introduced a novel architecture for PV laser power converters. The integrated series/parallel connection in stepped PV cells combines the advantages in current matching of common PV cell designs, namely, high tolerance against temperature changes and misalignment.

We presented a quantitative assessment of the misalignment tolerance by the comparison of the maximum acceptable misalignment, \(\text{MAM}_90\), of stepped, multijunction and multisegment PV cells. For an increasing number of segments, the stepped architecture approaches the performance of the ideal one-segment multijunction PV cell, whereas the \(\text{MAM}_90\) for multijunction converges to less than one third of this value. Calculations of the \(\text{MAM}_90\) for 2-, 3-, and 4-V GaAs-based stepped and multisegment PV cells revealed that for realistic numbers of segments (6, 9, and 12, respectively), high misalignment tolerances can be achieved with stepped PV cells.

Finally, we demonstrated the first realization of such devices by two-junction circular PV cells. Based on this example, the unique features such as the azimuthal path of the current in the bottom cell and the optical absorption in the subcells were discussed, and means to simulate and measure these features were presented. We studied the effect of segmentation and identified the six-segment device to be the optimal candidate for power-by-light systems.

In conclusion, it was demonstrated that the presented stepped approach combines the advantages regarding current matching from both multijunction and multijunction PV architectures. However, the epitaxial thickness and processing efforts increase with the desired photovoltage because more and more fully absorbing junctions are stacked. For practical applications that justify higher effort in fabrication, the presented approach has shown significant reduction of misalignment losses and can therefore increase performance.

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CONFLICT OF INTEREST

The Fraunhofer Society and four authors (A.W.B., S.K.R, S.P.P, and H.H.) filed a patent for the PV cell architecture presented in this work. The remaining authors declare no competing financial interests.

ORCID

Lukas Wagner @ https://orcid.org/0000-0002-6883-5886
Sebastian Kasimir Reichmuth @ https://orcid.org/0000-0002-4963-0236
Henning Helmers @ https://orcid.org/0000-0003-1660-7651

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SUPPORTING INFORMATION
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