OWPT2021 | Oral Presentation

OWPT Session 6

Wed. Apr 21, 2021 3:30 PM - 5:00 PM OWPT (Online)

[OWPT-6-02] Current Mismatch and Luminescence Coupling in Three-junction Photonic Power Converters with and without Back Reflector

〇Esther Lopez[1,2], Oliver Höhn [1], Meike Schauerte [1], David Lackner [1], Michael Schachtner [1], S. Kasimir Reichmuth[1], Henning Helmers [1] （1.Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany, 2.Instituto de Energía Solar – Universidad Politécnica de Madrid, Madrid, Spain）

In this work the coupling process efficiency in three-junction photonic power converters based on GaAs/AlGaAs rear-heterojunction subcells is experimentally quantified. A coupling process efficiency of 32 % ± 9 % from top and middle subcells to the limiting bottom subcell is found. Furthermore, it is evidenced how a back reflector affects luminescence coupling of these devices by re-directing photons that are emitted by the bottom subcell towards the upper subcells

The 3rd Optical Wireless and Fiber Power Transmission Conference (OWPT2021), Online, Japan, Apr. 19 - 22, 2021

Current Mismatch and Luminescence Coupling in Three-junction Photonic Power Converters with and without Back Reflector

Esther López [1),2)], Oliver Höhn [1)], Meike Schauerte [1)], David Lackner [1)], Michael Schachtner [1)], S. Kasimir Reichmuth [1)] and Henning Helmers [1)]
[1)] Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany
[2)] Instituto de Energía Solar – Universidad Politécnica de Madrid, Madrid, Spain
henning.helmers@ise.fraunhofer.de

***Abstract**: In this work the coupling process efficiency in three-junction photonic power converters based on GaAs/AlGaAs rear-heterojunction subcells is experimentally quantified. A coupling process efficiency of 32 % ± 9 % from top and middle subcells to the limiting bottom subcell is found. Furthermore, it is shown experimentally how a back reflector affects luminescence coupling in multi-junction photonic power converters by re-directing photons that are emitted by the bottom subcell towards the upper subcells.*

1. Introduction

Laser power converters or photonic power converters (PPC) are photovoltaic cells used in optical power transmission systems to supply power to remote loads. These devices need to provide common voltages of 3.3 V or 5 V to efficiently power downstream electronics, which can be realized by a series interconnection of multiple vertically stacked subcells. Ideally, in the "current match" case, all series-connected subcells absorb the same fraction of the incident light and, thus, generate the same photo current (assuming perfect collection of the photo-generated carriers) [1]. However, even in a perfectly designed device, in real world applications the operating conditions typically vary and e.g. temperature variations cause current mismatch between the subcells [2], [3]. As a consequence of the series connection, in this case the overall current of the device is limited by the subcell with the lowest photo current. Yet, luminescence coupling between the subcells can mitigate current mismatch by redistributing the photocurrent resulting in an increase of the current of the limiting subcell [4], [5].

In this work the coupling process efficiency in three-junction PPCs based on GaAs is studied and quantified experimentally, using the method proposed in Ref. [6]. Furthermore, back surface reflectors are implemented to enhance the luminescence coupling towards upper subcells by redirecting photons that would otherwise be lost in the substrate towards the upper junctions.

2. Devices and methods

To study luminescence coupling effects, we analyze PPCs based on three vertically stacked GaAs/$Al_{0.3}Ga_{0.7}As$ rear-heterojunction subcells. Two different epitaxial structures are designed to provide current match at 25 °C at two different wavelengths: 809 nm (structure A) and 845 nm (structure B). 4" wafers with these epitaxial structures were processed to PV cell devices (designated area A_{des}=0.054 cm²). Certain wafers were processed on substrate, whereas others were processed to thin film devices with an Au reflector directly beneath the photovoltaic cell structure. Further details of the processing can be found in Ref. [6].

Current-voltage (*I-V*) characteristics are measured at different irradiances under a pulsed laser source (pulse duration of 4 ms to minimize heating of the device under test) with 809 nm center wavelength and a FWHM of 3 nm [7]. A cryostat chamber was used for temperature dependent measurements over broad range. The data is used to determine the spectral response (*SR*) at the laser wavelength as a function of irradiance: *SR* can be directly derived from short-circuit current density J_{SC} divided by monochromatic irradiance G_{in}.

3. Results and discussion

Fig. 1 shows the measured irradiance dependent *SR* of structure A and structure B at 25 ºC under λ_0=809 nm laser illumination. The device designed to provide current match at λ_0 (structure A) shows the highest *SR*. Besides, within the measurement uncertainty, the *SR* is found to be independent of irradiance. On the contrary, in the current mismatched structure B the measured *SR* is lower and shows a logarithmic increase with irradiance of 5.3 % per irradiance decade (red trend line in Fig. 1). An estimation of the *SR* in absence of luminescence coupling for structure B at 25 ºC is shown in Fig. 1 by a red star symbol. This estimation is derived from external quantum efficiency (*EQE*) measurements, conducted under low irradiance levels where the luminescence coupling is very weak (quite below 1%) and its effect can be well neglected.

The observed increase in *SR* with increasing irradiance can be attributed to luminescence coupling between the subcell, as with increasing irradiance the subcells become more and more radiative [3]. In structure B, compared with structure A, the top and middle subcells are thicker, so they absorb more light under laser illumination, leaving a lower fraction of the incident light to be absorbed by the bottom subcell. The excess current of the top and the middle subcells radiatively couples into the bottom subcell.

The efficiency of this coupling process can be calculated using the difference between the estimated *SR* without luminescence coupling (red star) and the measured *SR* (red dots), and the difference between the estimated *SR* without luminescence coupling (red star) and the *SR* obtained for current match conditions (black dots) [6]. A coupling process efficiency of 32 % ± 9 % is obtained for the structure B at 25 ºC, for the highest irradiance provided by the 809 nm laser (G_{in} = 140 W/cm²). The given uncertainty was calculated according to the law for the propagation of uncertainty, taking into account wavelength variation in the laser emission (±2 %) and non-perfect current matching of the structure A at 25 ºC and 809 nm (0.4 %). The coupling process efficiency can be slightly underestimated as a result of estimating the *SR* without luminescence coupling from *EQE* measurements. Since luminescence coupling between subcells can never be completely suppressed under current mismatch conditions.

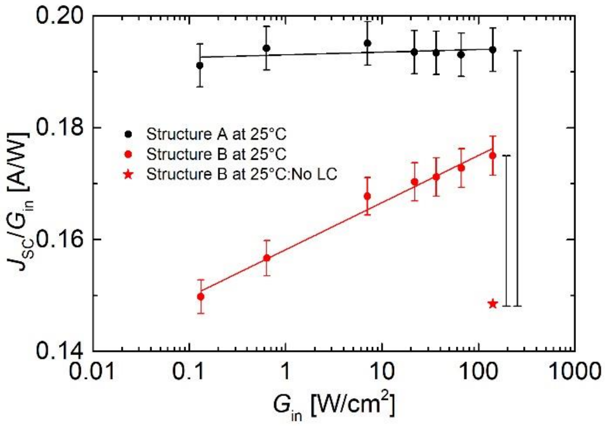

Fig. 1. Measured spectral response $SR=J_{SC}/G_{in}$ at λ_0=809 nm and 25 ºC for structure A and B. The red star represents the estimated value in absence of luminescence coupling.

To analyze how a back reflector affects the luminescence coupling in multi-junction PPCs, two cells with structure A (current match at 809 nm and 25 ºC) are compared: One processed on substrate, the other processed as thin film cell with a gold back reflector. Fig. 2 shows the irradiance dependency of the *SR* at 809 nm at temperatures below the design temperature 25 ºC. Hence, the top subcell is limiting the current for all shown data.

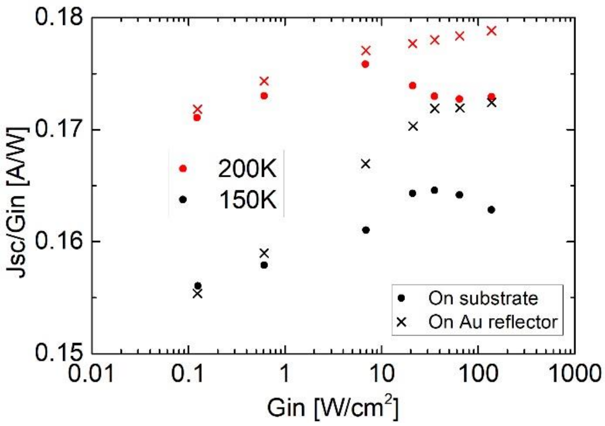

Fig. 2. Measured spectral response of multi-junction cells with structure A, at λ_0=809 nm and at temperatures of 150 K and 200 K, *i.e.* below the design temperature of 25 ºC. Measurements are carried out for cells on substrate and cells with Au reflector.

For the PPCs on substrate (closed circles), two regimes are found: At low irradiances below about 10 W/cm² the *SR* increases with increasing G_{in}; at higher irradiances above about 10 W/cm² *SR* tends to saturate. For the device with back reflector (cross symbols), the behavior at lower irradiances is similar. At higher irradiance, however, a significantly higher *SR* is observed when the back reflector is implemented. This increase compared with the cell on substrate is most pronounced at lowest temperature (150 K), and it increases with increasing G_{in}.

The observed behavior can be understood as follows: The back reflector redirects a significant fraction of the photons emitted by the bottom subcell that otherwise would be lost in the substrate. These photons now couple into upper subcells and increase their photo currents. That's why at higher irradiances the *SR* of the cell with reflector increases compared with the cell on substrate. At lower irradiances, even though the *SR* increases with increasing G_{in}, there is no difference between cells with and without back reflector. Consequently, the luminescence coupling to the limiting top cell which is responsible for this increase does not originate from the bottom subcell with back reflector, but rather originates from the middle subcell only.

4. Conclusion

The coupling process efficiency of photonic power converters based on three stacked GaAs/AlGaAs rear-heterojunction cells has been experimentally quantified and shown to be 32 % ± 9 % at 140 W/cm² illumination (809 nm) for the coupling from the upper two subcells to the limiting bottom subcell. In addition, it is shown how the implementation of a back reflector enhances luminescence coupling from an overproducing bottom subcell towards the top and middle subcells, as it redirects photons that would otherwise be lost in the substrate.

Acknowledgment

This work was partly funded by the German Federal Ministry of Education and Research (BMBF) through the project "Lightbridge" (16ES0788). Esther López acknowledges an Atracción del Talento Fellowship (2019-T2/AMB-12959) funded by the Comunidad de Madrid.

References

[1] S. Fafard *et al.*, Appl Phys Lett, **108**(7), p. 071101 (2016). doi: 10.1063/1.4941240
[2] H. Helmers *et al.*, in Proc SENSOR, pp. 519–524 (2015). doi: 10.5162/sensor2015/D1.4
[3] S. K. Reichmuth *et al.*, Prog Photovolt Res Appl, **25**(1), pp. 67–75 (2017). doi: 10.1002/pip.2814
[4] M. Wilkins *et al.*, J Appl Phys, vol. 118, no. 14, p. 143102 (2015). doi: 10.1063/1.4932660
[5] F. Proulx *et al.*, pss (RRL), **11**(2), p. 1600385 (2017). doi: 10.1002/pssr.201600385
[6] E. Lopez *et al.*, Prog Photovolt Res Appl (2021). doi: https://doi.org/10.1002/pip.3391
[7] S. K. Reichmuth *et al.*, in Proc 32nd EU PVSEC, pp. 5–10 (2016). doi: 10.4229/EUPVSEC20162016-1AO.1.2