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CHEETAH

Cost-reduction through material optimisation and Higher EnErgy outpuT of solAr pHotovoltaic modules - joining Europe's Research and Development efforts in support of its PV industry

Deliverable

D8.21- First functional, interconnected CIGS micro-concentrator modules demonstrating feasibility of 16 % conversion efficiency.

WP8 –Module development for ultrathin x-Si cells and thin-films.

Section 1 – Document Status

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Section 2 – Table of content

Section 3 – Executive summary

Description of the deliverable content and purpose

This report describes the methods and approaches that were employed in order to achieve the **first CIGS micro concentrator modules demonstrating feasibility of 16 % conversion efficiency**.

The objective is to manufacture functional mini-modules which can profit from the benefits of concentrated light. The benefits include the increase of overall efficiency due to the logarithmic increase of voltage proportional to light intensity, addressed in this report, and the saving of material to prevent future scarcity, addressed in deliverable report D8.19. These benefits can be enhanced by reducing the area of the device, which reduces thermal influence of the concentrated light.

The modules presented have been manufactured in a process which is close to the presently established method for interconnecting CIGS modules (w/o concentration) as was described in milestone report MS8. We decided to deviate from the more complicated design as proposed earlier in deliverable report D8.14 (M12) in order to reduce risk and to be as close as possible to the presently used industrial processes. An arrangement consisting of the interconnected module, a lenticular (lens array) and a positioner (lens holder) is included in the presented report.

Brief description of the state of the art and the innovation brought

Multiple mini modules were processed. To manufacture such a device, state of the art $Cu(In,Ga)(S,Se)_2$ layers stacks were used. The interconnection by laser and mechanical scribing is similar to standard CIGSe panel manufacturing, where different materials are deposited and processed onto a substrate forming a stack of materials in specific sequence: Molybdenum, P1 scribe, CIGSe absorber, buffer layer, i-ZnO, P2 scribe, TCO and P3 scribe. However, the main difference is in an additional P3 patterning step, the so called P4 scribe. With the addition of this process step it was possible to reduce the commonly used stripe width of 5 mm cell width down to narrower stripes between 50 and 800 µm. In figure 1, an example of the interconnection scheme utilized is presented.

Given the long and well defined geometry of the stripes, 1-dimensional concentration through spherical cylindrical lenses was considered as optimal for the proposed layout. The cylindrical lens is supported by a holder which serves also as positioner. Thus, the CIGSe mini-module, the lens array (or lenticular) and the positioner form the micro-concentrator PV device.

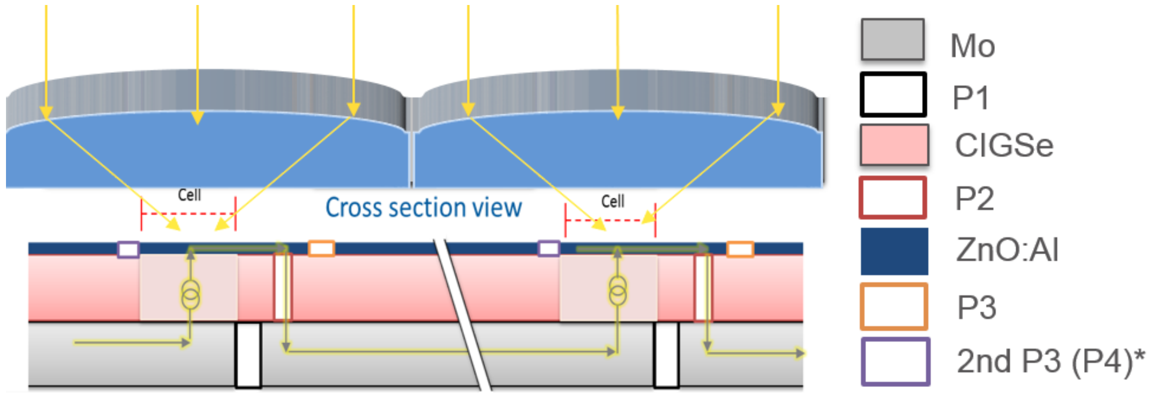


Figure 1. *Interconnection scheme for a* micro-concentrator PV device.

The electrical characteristics of the devices with and without the lens array were measured in a Class AAA solar simulator with simulated 1.5 AM illumination and compared obtaining a substantial increase in both fill factor and efficiency for the devices with lens.

Section 4 – Deliverable report

D8.21: First functional, interconnected CIGS micro-concentrator modules demonstrating feasibility of 16 % conversion efficiency.

The interconnection and module integration of CIGS micro-concentrator cells has been successfully completed by HZB following the interconnection scheme as proposed in the MS8 report. These sub-modules were tested to ensure good quality interconnection using multiple measurements such as microscopy, dark lock-in thermography and IV measurements under simulated solar light at standard conditions. Also, further processing like encapsulation and scribing for different cell sizes and layouts was carried out.

Multiple mini modules were manufactured following the previously mentioned interconnection scheme. To manufacture such a device, state of the art $Cu(In,Ga)(S,Se)_2$ thin film devices were used [1]. In state-of-the-art CIGSe panel manufacturing, different materials are deposited and structured onto a substrate forming a stack of materials in specific sequence as described in D8.19.

The P1 scribe was performed through laser ablation, whereas the P2 scribe was performed through mechanical scribing. For the presented devices, the P3 and P4 patterns were carried out through selective direct ablation of the TCO by means of picosecond laser pulses [2]. The implementation of a P4 scribe positioned before a P1 scribe limits the active area to the surface encompassed between the P4 and the P1 scribe. This causes the area before the P4 scribe to be isolated and therefore, unutilized. Thus, it was possible to limit the commonly used active area of 5 mm cell width down to 50 µm. However, due to the optical characteristics of the lenses at the focal length, an optimal stripe width of around 700 µm was found. Figure 2 shows an interconnected module following the presented concept and a zoom into the active area of one stripe (i.e. ~500 µm width).

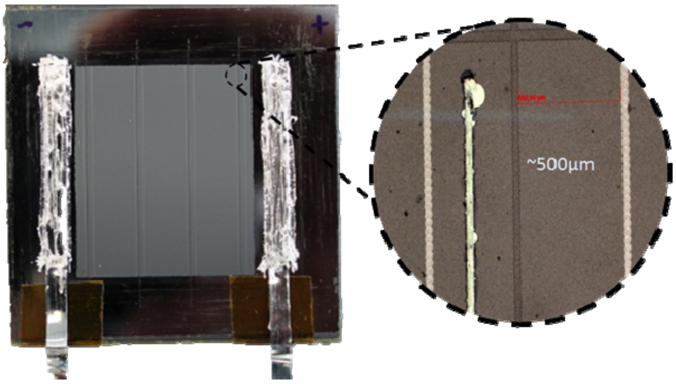


Figure 2. *CIGSe module for micro-concentration with narrow stripes of 500µm.*

The best submodules have been tested with the purpose of observing the electrical behavior at different concentrations. JV curves were obtained by solar simulation with STC light intensity at different concentrations, ranging from 1 to 11 suns (i.e. optimum design concentration) and compared against solar simulation at standard conditions (STC) obtained with assembled and unassembled CIGS micro-concentrator devices.

An assembled CIGS micro-concentrator device (e.g. figure 3) consists of an array of 4 interconnected cells in a photovoltaic module, a lenticular positioner and an acrylic lenticular for 1-D concentration, whereas the unassembled device consists only of 4 interconnected cells in a photovoltaic module.

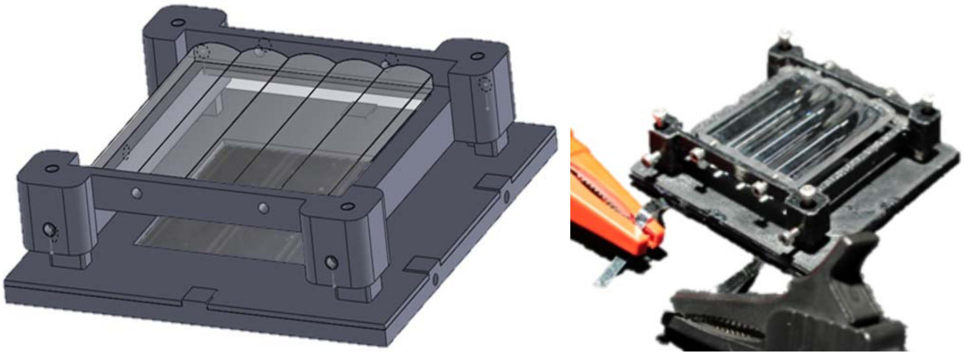


Figure 3. *Assembled CIGS micro-concentrator device.*

In figure 4, the respective concentration relations for this interconnection scheme of 1-D concentration are depicted. The maximum solar concentration in mW/cm^2 (PL,max) can be obtained from the ratio of the geometry of the lens array with respect of the solar cell times the solar irradiance at STC (Pϕ). Thus, by using a 7.52mm lens-pitch with a cell of 752 µm width, one can obtain 10 suns as maximum concentration (i.e. 1000 mW/cm^2). The measured concentration (PL,meas) is obtained indirectly measuring the current density at concentration over the current density at STC times the irradiance at STC.

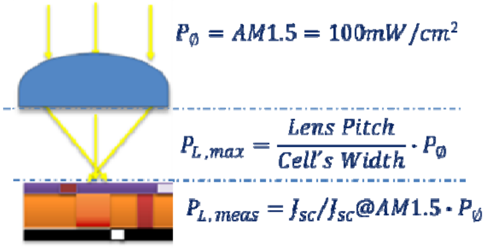


Figure 4: Incident light power before and after lens positioning and measured concentration.

Cell Width	$\frac{P_{L,meas}}{P_\emptyset}$	$\frac{P_{max}}{P_\emptyset}$	P_L/P_{max}
685 µm	5.86	10.98	0.53
488 µm	7.62	15.41	0.49
680 µm	7.34	11.06	0.66

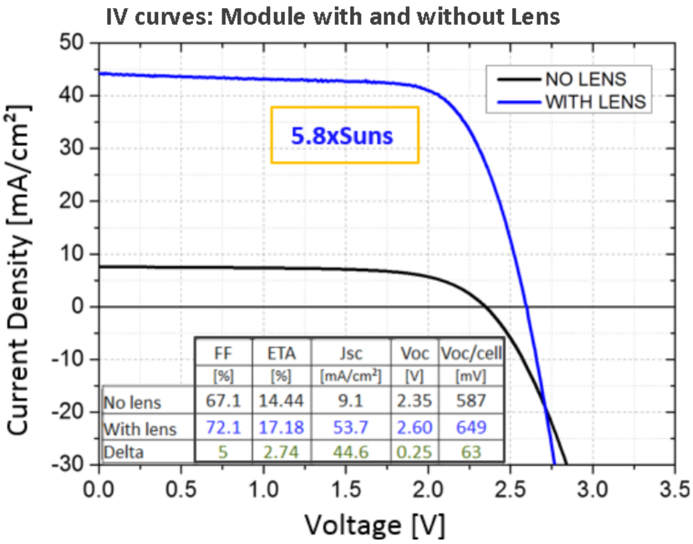
Table 1: Incident power depending on sample geometry and lens properties.

Table 1 show the best measured concentration obtained for the presented arrangement, reaching over 7.5 suns out of a maximum of 15.41 suns for 488µm wide cells. However, the best efficiency module had a 5.86 concentration factor out of a maximum of 10.98 suns. Furthermore, the best incident light ($P_{L,meas}$) relative to P_{max} of 0.66 (i.e. lens performance) was obtained for cells of 680 µm. The variations in this ratio are mostly dependent on lens adjustment and over-illumination, where the area of the focused light is larger than the cell´s width.

In figure 5, the main results are shown. The JV curves presented were obtained by means of simulated solar light at standard conditions for unassembled sub-modules (i.e. No lens) and for assembled micro-concentration devices (i.e. Sub-module, positioner and lenticular).

$$V'_{OC} = \frac{nkT}{q} \ln\left(\frac{XI_{SC}}{I_0}\right) = \frac{nkT}{q}\left[\ln\left(\frac{I_{SC}}{I_0}\right) + \ln X\right] = V_{OC} + \frac{nkT}{q}\ln X \qquad (1)$$

Assuming that light intensity is proportional to the photocurrent and given that the current density increased from 9.1 to 53.7 mA/cm^2 (i.e. 9.1 mA/cm^2 per cell with no lens), a measured concentration of 5.86 suns was obtained. Using formula 1 [3], the increase in Voc and efficiency can be calculated. The open circuit voltage increases logarithmically, therefore, for each cell of 587 mV and an ideality factor of 1.7, an increase in voltage of 70 mV per cell is calculated, therefore, for a total of 4 cells, an increase from 2.3 to 2.6 V is expected. As the Voc increases logarithmically and Jsc increases proportionally to light intensity, an increase in fill factor limited by the series resistance is also expected.



	FF [%]	ETA [%]	Jsc [mA/cm^2]	Voc [V]	Voc/cell [mV]
No lens	67.1	14.44	9.1	2.35	587
With lens	72.1	17.18	53.7	2.60	649
Delta	5	2.74	44.6	0.25	63

Figure 5 *JV curves of a monolithically interconnected sub-module with and without lenses.*

Finally, the efficiency obtained can be calculated with the measured values according to formula 2.

$$\eta = \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{in}} \qquad (2)$$

As starting value, the best sub-module for micro-concentration had an efficiency of 14.5 %. This efficiency was obtained following formula 2, where: no lens is placed, only the active area is considered and P_{in} equals P_{ϕ} (i.e. standard conditions AM1.5). After positioning the lens-array and employing the same formula, an efficiency of about 17 % was found, however, this time P_{in} equals 5.8, which is the light concentration measured ($P_{L,\,meas}$).

$$\eta = \frac{V_{oc} \cdot J_{sc} \cdot FF \cdot \frac{A_{jsc}}{A_1}}{P_{in}} \qquad (3)$$

This efficiency can be also expressed considering the aperture area or module area of the CIGS submodule and the lenticular area by employing a variation of previous formula. Thus, different areas can be considered for the calculation of efficiency using formula 3, where: P_{in} equals P_{ϕ}, A_{jsc} is the originally employed area for the measurement (if necessary) and A_1 is either the inactive plus active material (i.e. module area) or the area of the incident light onto the lens-array (i.e. lenticular area). Hence, considering the module area an efficiency of 13.2 % was obtained and considering the lenticular area an overall panel efficiency of 10.1 % was calculated. Formula 3 is employed to reduce variations due to light soaking or misalignments from measurement to measurement.

There are multiple ways in which one can improve the performance of the presented device to go beyond 16 % according to the target in D8.21. These include the usage of better deposition techniques, better concentrator lenses and better lens adjustment. By employing the baseline process for co-evaporation of CIGSe in **HZB**, an initial efficiency of 14.5 % from interconnected control sub-modules was obtained. However, by employing optimized processes, this efficiency – at state-of-the-art – could be improved by up to 5.3 % absolute as e.g. compared to the record efficiency of a 7 x 5 cm² CIGS mini-module as recently reported by Solar Frontier this year, i.e. 19.8 % [4]. Thus, the efficiency of 10.1 % obtained based on the lens area would increase up to approx. 15.4 %. Furthermore, by employing an automatic lens positioning and different material lenses with higher transmission and with narrower concentration width, it should be feasible to improve the optical efficiency of the lenses from 53 – 66 % to >90 %. Therefore, an improvement of at least 24% relative efficiency can be added to the theoretical results obtained employing high efficiency deposition techniques, thus obtaining a 19 % overall efficiency mini-module for micro concentration.

A different approach was conceived by **ZSW** in order to obtain even higher efficiencies by employing 2-dimensional light concentration (dot cells). A module array of 67 rows with 21 interconnected dot cells was realized. With a size of 1 x 1 mm² and an active area of ≈ 100 x 100 µm², each cell has been designed to be operated at up to 100 suns by 2D light concentration. The best electrical characteristics present a fill factor of 73 % at 60 suns with an open circuit voltage of 760 mV. Thus, an overall efficiency beyond 17 % can be already calculated. These results are taken from single cells, but contacted through monolithic interconnection. More results regarding this approach are shown in work package 9 deliverable D9.5.

In summary, it has been shown that functional CIGSe micro concentrator modules can be produced with various interconnection methods, reaping the benefits of light concentration on CIGSe absorbers. Furthermore, by employing better deposition processes, better lens positioning and better quality lens arrays, we consider it well feasible to go beyond 16 % conversion efficiency, meeting the objective of this deliverable.

References:

[1] C.A. Kaufmann, T. Unold, D. Abou-Ras, J. Bundesmann, A. Neisser, R. Klenk, R. Scheer, K. Sakurai, H.-W. Schock, “Investigation of coevaporated Cu(In,Ga)Se2 thin films in highly efficient solar cell devices”, Thin Solid Films, vol 515, Issue 15, pp 6217-6221, 2007.

[2] M. Schüle, C. Schultz, V. Juzumas, K. Stelmaszczyk, M. Weizman, C. Wolf, N. Papathanasiou, B. Rau, R. Schlatmann, V. Quaschning, B. Stegemann, F. Fink, ”Laser Patterning of Cigs Based Solar Cells Using Nano- and Picosecond Pulses - Possibilities and Challenges”, 28th European Photovoltaic Solar Energy Conference and Exhibition, 3BV.5.39, p. 2302 – 2306, 2013.

[3] B. Reinhold, M. Schmid, D. Greiner, M. Schüle, D. Kieven, A. Ennaoui, M.C. Lux-Steiner, “Monolithically Interconnected Lamellar Cu(In,Ga)Se2 Micro Solar Cells Under Full White Light Concentration”, Prog. Photovolt: Res. Appl., 23: 1929–1939, 2015. Doi: 10.1002/Pip.2611.

[4] www.photovoltaic-conference.com. (2017). Finger Resistance. [Online].Available: https://www.photovoltaic-conference.com/images/News/EU_PVSEC-2017-NewsNo18/EU_PVSEC-2017-NewsNo18.html. [Accessed: 28- Nov-2017].