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Design and fabrication of a micro CPV system based on Cu(In,Ga)Se₂ microcells array

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ABSTRACT

From few millimeters to few hundreds of micrometers, solar cells used in CPV systems are made smaller and smaller, to benefit from the lower influence of the temperature and series resistance. We propose in this work microconcentration systems adapted to thin film microcells arrays. Due to the miniaturization, the complete system is expected to be very compact, lightweight, enabling a simple tracking. First, a numerical study has been performed to evaluate an optimal design with only plano-spherical microlenses with a geometrical ratio of 100x and an acceptance angle around $\pm 3^\circ$. Second, a fabrication process has been developed to realize the designed system. Arrays of 2500 microlenses with a diameter between 300 and 500 μm and a focal length around 1mm have been created. Finally, we propose a first prototype coupling 2500 microcells and microlenses arrays for middle concentration applications.

Keywords: Photovoltaic, CPV, Concentrator, CIGS, Microcells, Microlenses

1. INTRODUCTION

The domain of the low and middle concentration is dominated by Si solar cells, adapting flat-plate technologies to a use under concentration or developing new approaches (MEPV concept developed by Sandia¹). We propose to use a low to middle range concentrating system on a well-known PV material yet rarely used in CPV applications, Cu(In,Ga)Se₂. Recently, a record of 22.3% has been achieved, by Solar Frontier under AM1.5, making CIGS cells more efficient than polysilicon cell (record of 20.4%²). Moreover, because Cu(In,Ga)Se₂ is a thin film material, it has the intrinsic advantage that Cu(In,Ga)Se₂ solar cell arrays could be directly fabricated on the substrate by a top-down or a bottom-up approach, such as impression techniques. We studied⁽³⁻⁵⁾ the miniaturization of the Cu(In,Ga)Se₂ solar cell in order to develop efficient concentrator cells. The present work develops a prototype concentrating system adapted and integrated to these thin films microcells arrays.

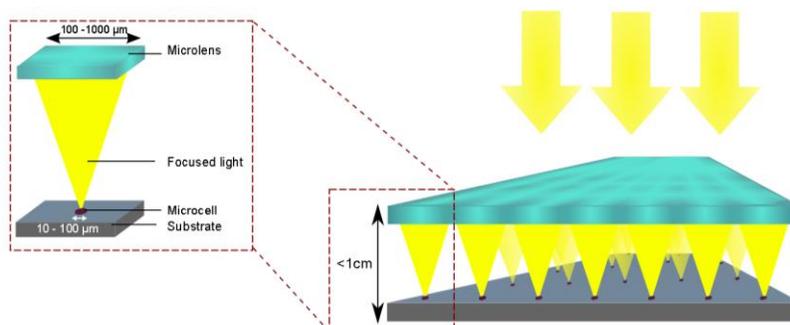


Figure 1. Sketch of the thin film microconcentrator concept

2. A CU(IN,GA)SE₂ CONCENTRATOR SYSTEM

Our work on Cu(In,Ga)Se₂ microcells has covered different aspects. After a first theoretical study of miniaturization effect⁶, we fabricated proof of concepts devices with dimensions from 5 to 500 μ m, made of coevaporated absorbers and a structured window layer to create the microcells. The test under concentrated illumination highlighted an increase of the conversion efficiency of 2% absolute for each decade of concentration (16% efficiency under 1x and 21.3% efficiency under 475x, a relative increase of the efficiency of 30%), if parasitic losses are kept low, and very limited temperature elevation under high flux³. We also tested Cu(In,Ga)Se₂ microcells with absorbers grown by low cost techniques, such as electrodeposition⁷. This technique allows to demonstrate the proof of concept but fails to save material. Then, we fabricated localized microcells using etching techniques and we assessed that edge recombination is very limited in these devices, making them adequate and efficient microconcentrator cells⁴. These microcells are closer to an application as the absorber layer is not kept intact on the substrate, but patterned to create mesa diodes and save material. Finally, a technique of localized grow of Cu(In,Ga)Se₂ is being developed, which will lead to real material saving.

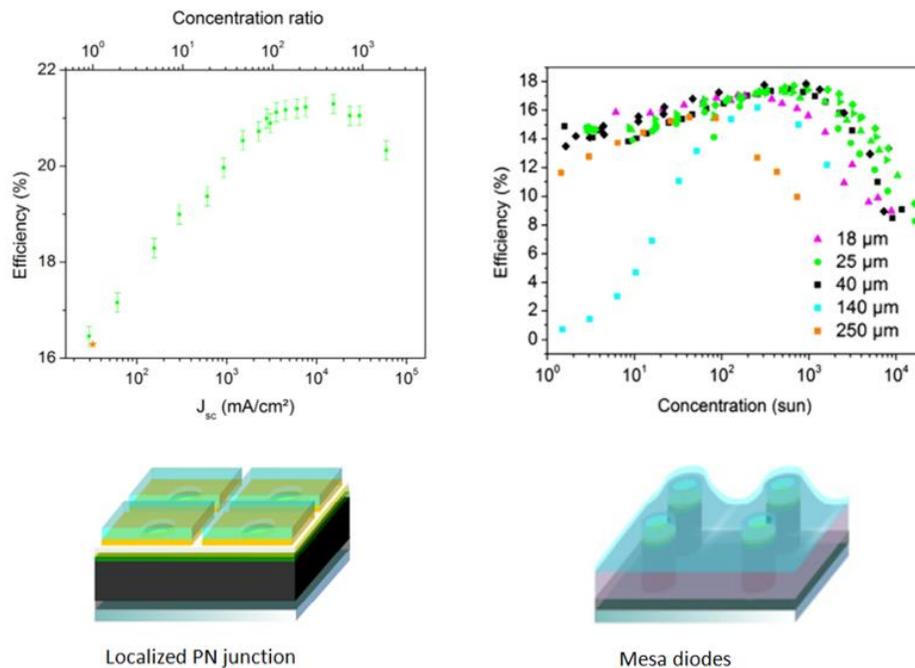


Figure 2. Top left, efficiency as a function of short-circuit current density or concentration ratio for the best microcell of diameter 50 μ m. Measurements under 532nm laser light. The orange star corresponds to AM1.5G measurement³. Top right, efficiency as a function of concentration ratio for mesa diodes with various diameters⁴. Bottom left and bottom right, illustration of the generation 1 and 2 of the Cu(In,Ga)Se₂ microcells

3. NUMERICAL STUDY OF A CONCENTRATING SYSTEM

In this work, we decided to design the system only with plano-spherical lenses. Spherical lenses are not the best system because of aberrations but they are easier to fabricate as an array, which leads to lower costs, especially for a large area production. The first system has been designed to achieve an increase of the absolute efficiency close to 4%. Based on Paire *et al*³, we have chosen an optical system with a geometrical ratio of 100. The geometrical ratio is defined as the ratio between the surface of the primary lens and the surface of the microcell. To design the system, we used a ray tracing software, Zemax OpticStudio.

To have a low cost sun tracking system, our optical system needs to have a large acceptance angle. So, based on a geometrical ratio of 100x, our objective is to obtain the maximum optical efficiency of the system, maintaining the

acceptance angle as high as possible. The influence of the number of optical elements and the geometrical parameters of the spherical lenses have been studied ^{8,9}. To design a very thin optical system, we have chosen to work with a high index material, the Polycarbonate (PC).

We achieved a final design of 1mm thickness, with two levels of optics and a theoretical concentration factor of 85x and an angular acceptance of +/-3°, without anti-reflective coating. With an anti-reflective coating, we can expect a concentration factor around 95x.

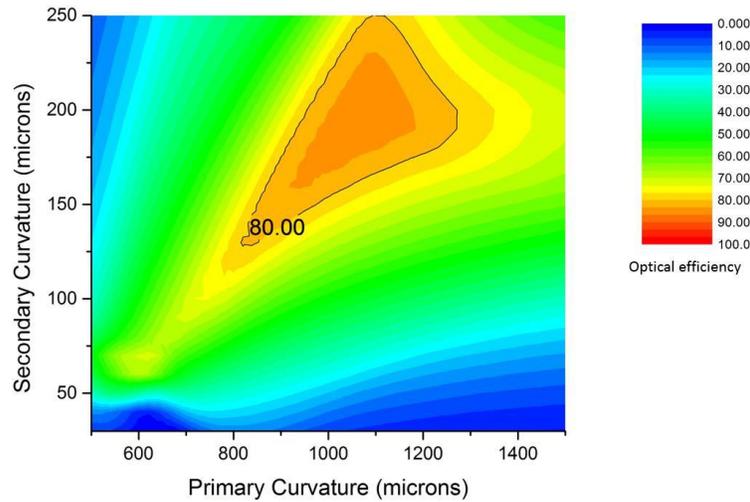


Figure 3. Map of the optical efficiency, depending on the radius of curvature of the primary and secondary lenses, for an incident angle of 3°

4. ESTIMATION OF PERFORMANCES IN REAL CONDITIONS

Using a MATLAB code that we developed, we evaluated the performances of such a system in real conditions, at different locations. The code is based on four key parameters: meteorological data (from NREL NSRDB), number of axis of the tracking system, the optical parameters of the designed system and the electrical behavior of the solar cell.

To calculate the average increase of efficiency and the annual production of our system we chose a solar microcell working at 17% efficiency under AM1.5G. The optical system used is described in the numerical study, taking into account the angular dependency of the optical efficiency and an anti-reflective coating. The sun tracking system is a two-axis tracker.

In sunny regions, the increase of the efficiency is important, which results in a system being more efficient than a standard flat panel on a 2-axis tracker. Moreover, it saves rare-earth material which supply will be difficult in the coming years ¹⁰⁻¹².

Table 1: Annual production of a micro-CPV system based on CIGS solar microcells

Location	Meteorological Data		CIGS microcells on 2-axis tracker		CIGS flat panel on 2-axis tracker
	DNI (%)	DNI (kWh.m ⁻²)	Average absolute efficiency (%)	Production (kWh.m ⁻²)	Production (kWh.m ⁻²)
Las Vegas	81	2726	+ 3	540	505
San Francisco	73	2165	+ 2.3	427	415
Seattle	60	1498	+ 0.7	294	302
New-York	56	1415	+ 1.2	277	303

5. PROTOTYPING

5.1 Fabrication process

To fabricate our microlenses we use the thermal reflow process. First, cylinders with a controlled diameter and height are fabricated using photolithography. Then, these structures are melted in an oven and take a spherical shape by minimizing the surface energy. Adjusting the dimensions of the initial cylinders allows us to control the geometrical parameters of the microlenses, such as the radius of curvature.

To show that the photoresist itself can be used to fabricate the optics of our prototype, at a laboratory scale, and be able to concentrate the light under AM1.5, we realized a first coupling experiment. We coupled a 16 μm diameter microcell with a 500 μm lens. The numerical evaluation of this system allowed us to expect not more than 38x. We obtained a concentration factor of 33x under a non-CPV solar simulator, which confirm that the photoresist can be used as an optical material for our prototype⁹.

Finally, we fabricated an array with 2500 microcells of 54 μm diameter, all connected in parallel, for a total active area of 5,72x10⁻²cm². On top of these microcells we fabricated 2500 secondary microlenses. On the other hand we fabricated the 2500 primary microlenses on a 1mm glass substrate.

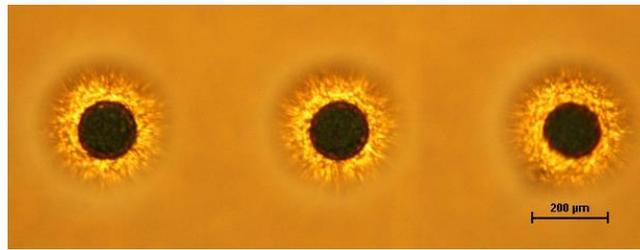


Figure 4: 54 μm microcells through secondary lenses

5.2 Coupling 2500 microcells and microlenses arrays

To couple the two arrays, we used a mechanical set-up composed of two angles to adjust the parallelism of the two substrates, two axis and one angle to align the optical axis of the primary and secondary lenses, and one axis to adjust the height of the primary lenses. The entire set-up has been installed under an AM1.5G solar simulator. The best alignment of the two arrays has been adjusted by maximizing the output current. J-V curves have been measured for different configurations, results are presented in Figure 5 and Table 2.

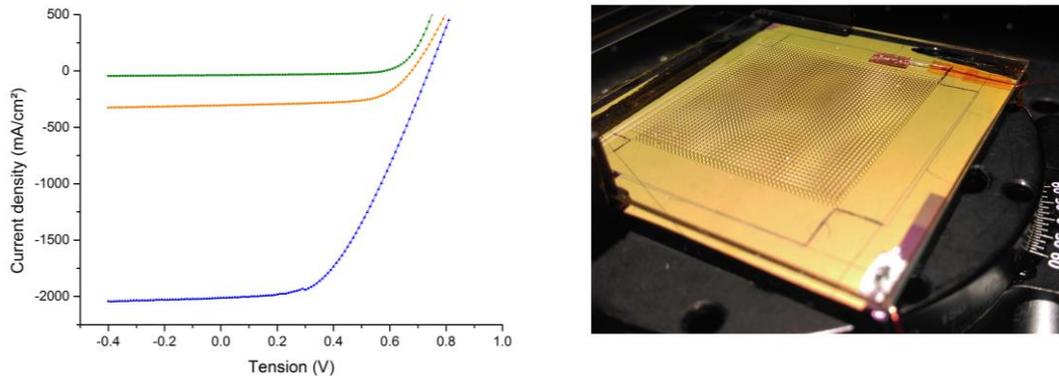


Figure 5: Left, J-V curves of the reference sample (green), reference sample and secondary optics (orange) and full system (blue). Right, picture of the first prototype under a solar simulator AM1.5G

Combining the array of microcells and the two arrays of optics, we achieved a concentration ratio of 65x, for a theoretical value of 85x. The difference between theoretical and experimental value can be mainly explained as we use a non-CPV solar simulator and the precision of the alignment set-up.

Concerning the electrical behavior of the microcells, we observe an increase of the open circuit voltage of +165mV. The fill factor also increases from 50% to 64% when the secondary lenses are added, due to the lower contribution of the shunt resistance. Unfortunately, the quality of our contacts is not good enough to be able to extract the high current density generated when the primary lenses are aligned, the series resistance is too strong and so the fill factor drops to 52%. The initial low fill factor, due to the fabrication process, and the bad quality contacts are being improved.

Table 2: Jsc, Voc, Fill Factor and concentration factor of the first prototype

	Jsc (mA.cm⁻²)	Voc (mV)	FF (%)	C factor (exp)	C factor (th.)
Reference array 2500 microcells	30,6	580	50	1	1
Array + secondary lenses	305	675	64	10	24
Array + secondary + primary lenses	2011	745	52	65	85

6. CONCLUSION

We propose a new type of concentrated photovoltaic system based on thin film microcells. A numerical study has been performed to design a very simple micro optical system based on microlenses, adapted to these microcells.

An estimation of the annual production of such a system, depending on the location, has been realized and shows that this system can be efficient in sunny region.

The measurements of the prototype showed good results. Improving the measurement set-up and the alignment of the arrays, we expect to achieve the theoretical performances of the system.

This concentrating system is a promising CPV solution for low and middle concentration because of easy microcells array fabrication associated with a compact and lightweight concentrating system.

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