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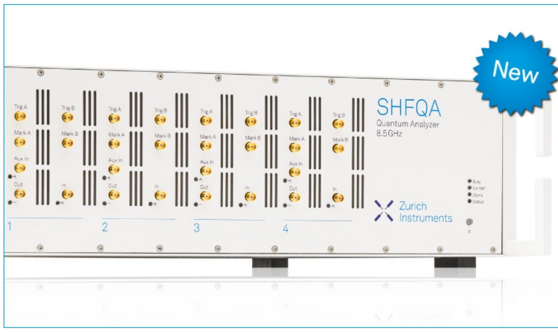

Update on Project ALCHEMI – A Low Cost HCPV Module for 1000 Sun Operation

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Abstract. Project ALCHEMI is a Solar Era.Net funded European collaborative project, which is developing a low cost, high efficiency HCPV module using a previous design developed by Fullsun PV. In this project, the 625 sun Gen 1 module has been redesigned to operate at 1000 suns and further improved by the utilization of state of the art 3 junction solar cells from three different vendors. Through use of ~42% efficient cells, it is expected to achieve module efficiencies of >37%. This paper describes the cell and module test and assembly process and initial evaluation of how the next generation of module will be improved still further through another iteration of the design of the secondary optical element (SOE).

INTRODUCTION

This paper provides an update on progress in the European collaborative Solar Era.net funded project ALCHEMI, which is manufacturing novel, low cost, HCPV modules that operate at ~1000 suns, and will demonstrate a DC module efficiency of >37% under Standard Test Conditions (STC) [1]. The novel, low cost design of the ALCHEMI module enables a manufacturing process that will achieve costs <€0.9/Wp (<$1/Wp) in large production volumes, exploiting the use of surface mount technology and pick and place (PnP) tools, as are widely used in the LED manufacturing industry. At the time of writing, the modules are currently at an advanced stage of construction and will be characterized on-sun at the University of Cyprus for an extended period, and CSOC and CSTC power ratings will be determined allowing a comparative analysis against conventional PV, other HCPV technologies, including Fullsun's Gen 1 modules, installed side-by-side in the same location.

MODULE DESIGN

The ALCHEMI HCPV module is constructed from aluminium and uses a silicone-on-glass (SOG) primary optical element (POE) and a silicone secondary lens (SOE), which is moulded directly over a 3J solar cell. For this project, three types of 3J solar cell have been selected for evaluation in the modules on-sun: a) 3C44, a triple-junction upright metamorphic design of GaInP/GaInAs/Ge from AZUR; b) Solar Junction triple-junction with ~1.0eV dilute nitride bottom cell grown on GaAs; and c) IQE's lattice matched classic GaInP/Ga(In)As/Ge triple-junction. A typical histogram demonstrating cell efficiency distribution from a single wafer is shown in Figure 1.

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All of the modules' internal components are surface mount devices (SMD) allowing assembly onto an insulated metal substrate (IMS) backplane, which is an integral part of the module's construction. This use of industry standard pick and place (PnP) assembly machines means that no specialist robotic equipment is needed for this assembly stage and the cost of factory Capex can be driven down substantially. The ubiquity of PnP machinery also means that the process is easily scalable, providing a clear roadmap to the manufacturing costs described above.

CELL PROCUREMENT & TEST

Solar cells have been procured through the channels described above, and in each case wafer maps of fundamental cell parameters have been generated to allow devices to be binned by cell performance (efficiency), allowing like for like cells to be populated in individual modules. Figure 1 below shows the frequency distribution of cells on a single wafer for one of the cell vendors. It can be seen that the cell efficiencies are close to the state of the art for similar devices operated under typical high concentration conditions [2]. Each of the cell vendors' devices have been binned in this way, and the project will assemble 10 ALCHEMI modules following the testing of 10 PCBs populated as follows:

5 – Azur Space
4 – Solar Junction
1 – IQE/UPM

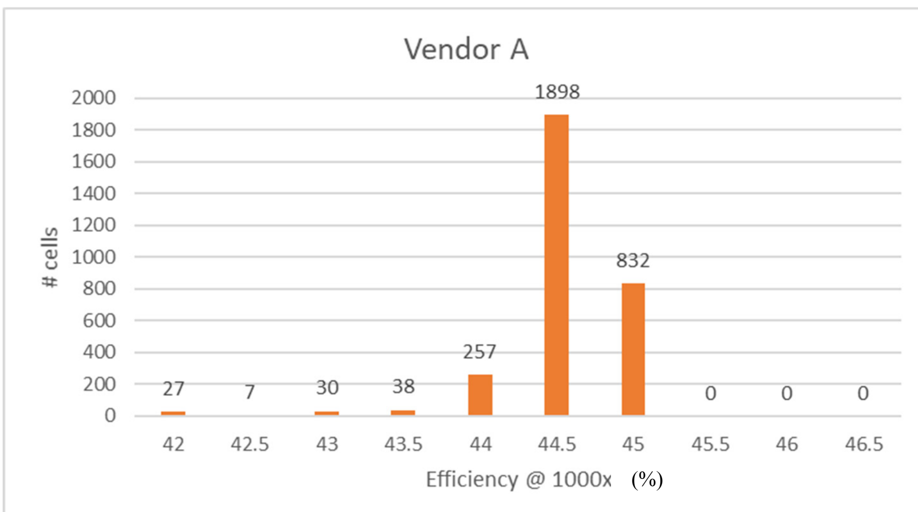

FIGURE 1. Cell efficiency distribution histogram for one of the types of solar cell chosen for this project. The choice of cell has clearly enabled a much higher efficiency to be achieved compared with those used in Gen 1 of the module design (typically ~37%).

An innovative refractive primary optic has previously been designed and optimised for operation at 1000 suns with the three types of multijunction solar cell that have been chosen for the project, and have been described previously [1]. The optics define the final dimensions of the solar cell, which is ~$1.3\times1.3mm^2$. A bespoke front grid design has been optimised to maximise output from these cells, and the redesigned module optical train, see Figure 2 below for one of the triple junction solar cell designs. Two of the solar cell suppliers use conventional Ag-metal front grids whereas the third uses a low-cost (Al-based) metallization. In order to ensure the compatibility of this metal stack with the gold wire-bonding process, bondability and pull strength tests where conducted and passed. Solar cells were wire bonded with gold wires of 25 µm in diameter, and the average pull force needed to detach the wires was 5 grams, is a factor of 2 larger than required by the standard [3].

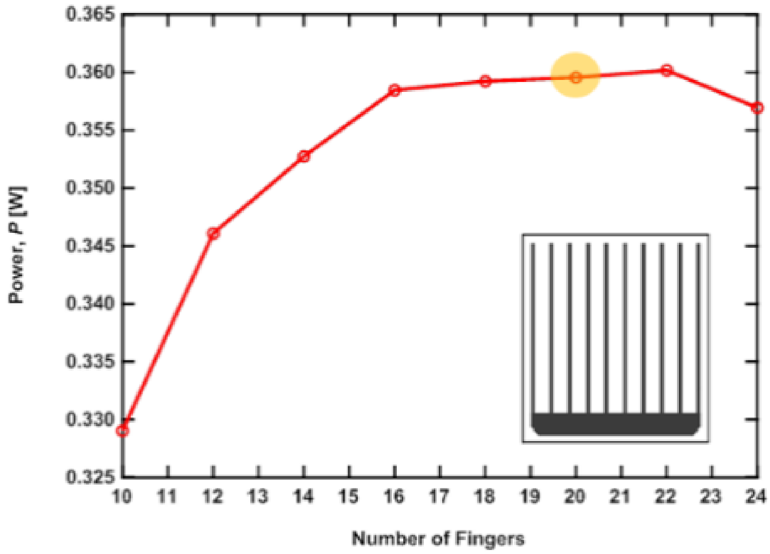

FIGURE 2. Results of the optimization process for the front grid considering the irradiance distribution of our optical train and a solar cell structure from Solar Junction Corporation (USA).

In addition, accelerated degradation tests are underway using climatic chambers at the Technical University of Madrid, to assess the reliability of these solar cells. A cohort of 20 multijunction solar cells is going through temperature step-stress ageing tests where devices are subjected to increasing temperatures starting at 90º up to 160ºC, in 10º deltas [4]. The upper limit for the temperature range was chosen not to introduce additional failure mechanisms that would never appear under real operation. HCPV working conditions are simulated by forward biasing each solar cell –through a dedicated current supply– at the same current density they would handle at the nominal concentration (i.e. 1000 suns, ~14A/cm^2) [5]. Temperature steps were stopped either when a specific number of failures occurred or when the time limit for the step was reached. Failure is defined as a power loss of 10% at MPP. Even though the best way to monitor such loss would be to measure the illumination I–V curve at 1000X (nominal concentration), this cannot be done easily for 20 devices inside a climatic chamber keeping standard conditions in all measurements. Instead, the evolution of solar cells is monitored recording the dark I–V curve at regular time intervals during the test. Prior to the beginning of the test, a calibration study was carried out to determine the correspondence between dark and 1000x illumination I-V curves. In this respect, failures are tracked monitoring the increase in recombination current throughout the test [5].

MODULE ASSEMBLY

The new refractive optic design has been utilised to procure silicone-on-glass (SOG) primary optics (POE), which are used in the assembly modules, along with a silicone secondary lens (SOE). Unlike the Gen 1 625x module that utilised 391 solar cells, weighed about 4kg, and was 48mm deep, the increased concentration factor of the ALCHEMI module means that we have a reduced number of solar cells to assemble, 234, which should lead to material cost savings but at the expense of a slightly deeper module (51mm) with a marginal increase in module weight.

Lens prototypes and solar cells were investigated experimentally. Figure 3 shows the resulting short circuit current I_{SC}, fill factor and maximum power P_{MPP} when illuminating a triple-junction solar cell with secondary optics through a Fullsun Fresnel lens. The measurement was carried out at the CPV sun simulator [7] at Fraunhofer ISE. The measurements resulted in an optimum cell-lens distance of 50 mm. When comparing to the optical simulations discussed in [1], the measurement under the sun simulator matches well to the simulation (where a standard sun spectrum was assumed) with a slightly higher (0.8 mm) optimum cell-lens distance than expected from the optical simulations. However, it matches well to the module height chosen.

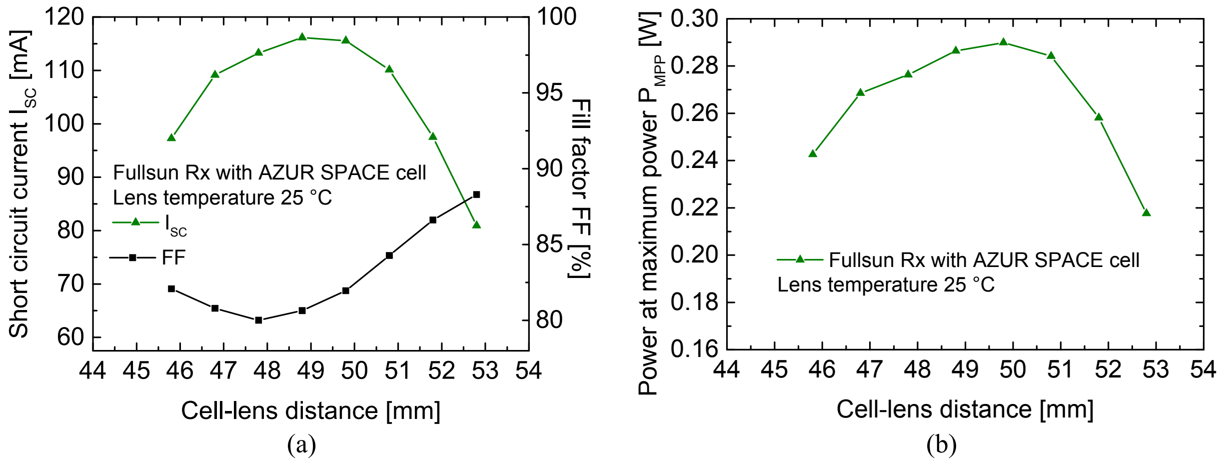

FIGURE 3. Measurement of the power output at different cell-lens distances. The measurement was carried out at the Fraunhofer ISE sun simulator for CPV modules. (a) Characteristic curve for the short circuit current and the fill factor versus cell-lens distance. (b) The maximum power output versus cell-lens distance. The temperature of the lens was 25 °C. The cell-lens distance is defined as the distance between front side of the solar cell and the rear side of the lens plate's glass carrier.

Several of Fullsun's previous Gen 1 HCPV modules, which operate at a concentration ratio of ~625x, with a DC module efficiency of ~30% using 37% efficient triple junction solar cells, have been transferred to the University of Cyprus, where they have been mounted on one of the PV Technology Lab's high precision 2-axis trackers. This will permit these modules to be evaluated on-sun in the same location that the ALCHEMI modules will be tested, to act as a direct benchmark. A close up image of one of the Gen 1 modules is shown in Figure 4. The PV Technology Laboratory at the University of Cyprus has the requisite inverters, IV tracers and datalogging infrastructure to enable both on- and off-grid (i.e. open-circuit) measurements to be carried out. The tracking accuracy is monitored by the BPI-TA1 sensor. A pyranometer and a pyrheliometer are used to measure the global and direct normal irradiances (GNI, DNI) respectively. The SolarSIM-D2 device is used for the spectrally resolved DNI, aerosol optical depth and precipitable water measurements. Maximum power point characteristics will be recorded on the DC (current and voltage) and AC (power) sides of the system using electrical transducers that are connected to a reliable data logging system. Thermal measurements are taken from the Fresnel lens' surface (close to the edge) and the aluminium rear surface. Meteorological measurements are acquired and stored through the data acquisition platform. Such measurements consist of the ambient temperature, wind speed and direction, relative humidity, pressure and rainfall. IV curves are taken using a PVPM1040X IV tracer. The Fullsun Gen 1 modules will be left in place on the tracker, and operated alongside ALCHEMI modules, to permit a direct comparison and demonstration of the superior performance of the ALCHEMI module. It is anticipated that the ALCHEMI modules will be in place and on-sun by mid 2019, following indoor module testing that will be carried out at ISFOC [6]

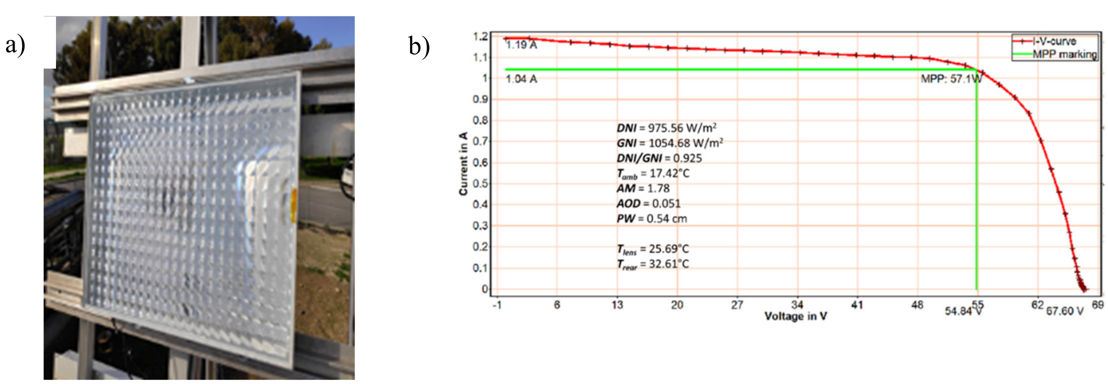

FIGURE 4. a) Image of Gen 1 module on tracker at UCY in Cyprus, and b) Initial on-sun module IV curve of this module, confirming previous performance

FUTURE MODULE IMPROVEMENTS

The modules include a silicone dome lens SOE, developed previously for the lower concentration Fullsun Gen 1 module. For the ALCHEMI project this SOE was to be maintained for cost reasons and the POE optimised for use with this SOE. A systematic approach to further improvement of the overall optical system performance would include a simultaneous optimisation of both POE and SOE. This would, however, be out of the scope of the ALCHEMI project. Instead, we provide example cases showing that even a redesign of the SOE alone without any further changes in the rest of system bears the potential for further improvement in terms of generated photocurrent. Similarly, a different approach to POE design is proposed below. The chosen figure-of-merit is the short circuit current, normalized by the POE aperture, evaluated using the spectral response of the 3J solar cell and spectrally resolved raytracing simulations of the irradiance distribution on the cell area. The result of a redesign of SOE, the modified SOE geometry "Gen 3, beta" is shown in Figure 5 (a) together with the existing Gen 1 SOE. The modified SOE is broader and steeper than the Gen 1 SOE. As a trade-off to the increase in peak performance under ideal alignment, the acceptance angle is slightly decreased. Figure 5 (b) shows the performance of the Gen 3 SOE design as compared to the Fullsun module and the ALCHEMI module with the Gen 1 SOE design.

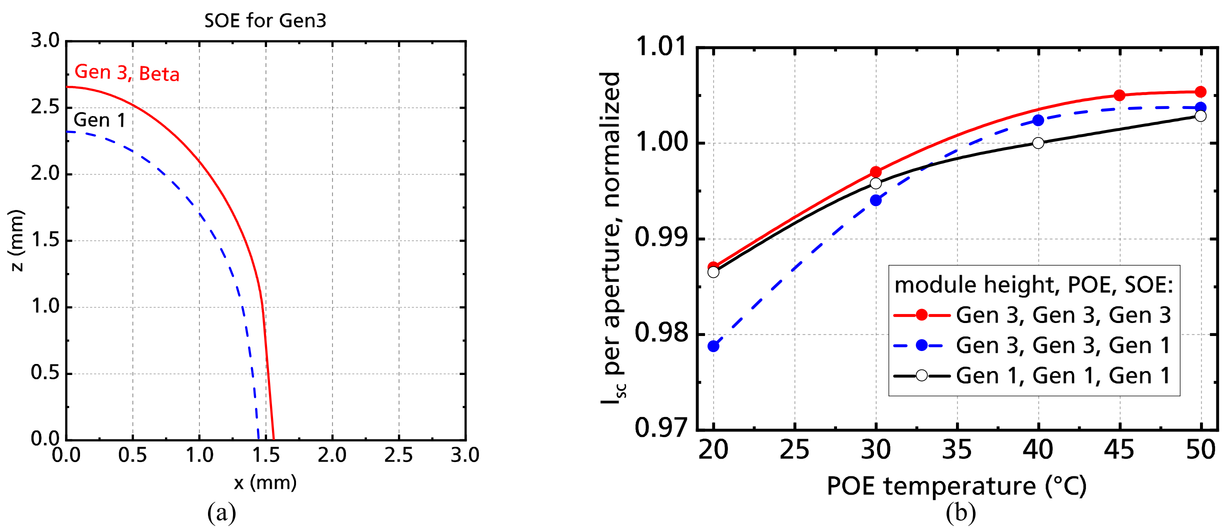

FIGURE 5. a) The design shapes of the modified Gen 3 SOE (red line) and the currently used Gen 1 SOE (blue dashed line). Shown are the design shapes at the silicone casting temperature. b) Short circuit current per POE aperture area, normalized to the case of the reference Fullsun module (Gen 1) at 40°C vs. expected operating temperatures (= temperature of the POE) for the ALCHEMI module with two different SOE – the currently used Gen 1 SOE with its design shape (●, blue dashed line) and the modified Gen 3 SOE at its design shape (●, red line). The bullets correspond to simulated cases, whereas the spline lines are guides for the eye. For reference, the behavior of the Fullsun's Gen 1 module is shown in black. The module height in the simulated cases differs between the ALCHEMI module and the Fullsun reference module.

As evident from Figure 5, the system is susceptible to changes of the operating ambient temperature and the resulting lens temperature, with an optimum around the casting temperature of SOG lens, typically around 45°C. This is not surprising as this is the intended operating point, where the Fresnel lens retains its design shape. Here, we applied a method for temperature adaption of a SOG Fresnel lens to different operating temperatures presented previously in [8], which allows the demonstration of two major improvements - (i) shift the optimum operating point away from the predefined casting temperature, e.g. to a lower operation temperature, and at the same time (ii) mitigate the temperature susceptibility around the new operation optimum. To demonstrate the impact on system performance we designed a completely new point-focusing Fresnel lens, which would be fabricated at 45°C, but is adapted for operation at 30°C and an operation range between 15 and 45°C. The simulated temperature behavior presented in Figure 6 shows both aforementioned improvements, expected with a temperature adapted lens. It should be pointed out, that no system optimization was carried out. A temperature adapted design can be suited to any desired mean temperature and temperature range of operation.

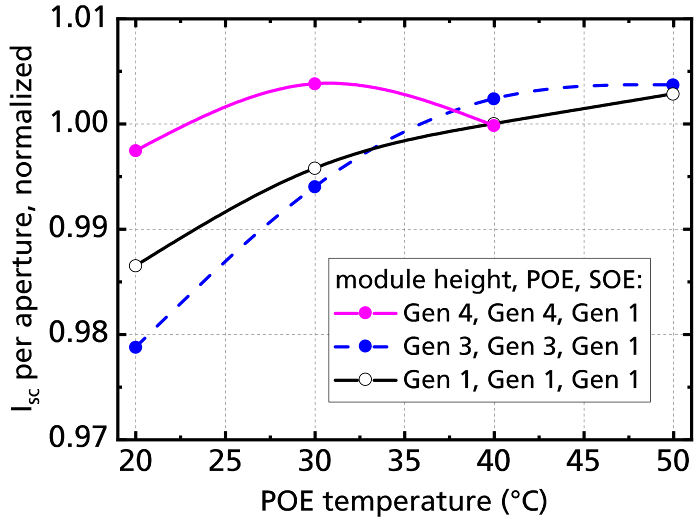

FIGURE 6. Short circuit current per POE aperture area, normalized to the case of the reference Fullsun module (Gen 1) at 40°C vs. expected operating temperatures (= temperature of the POE) for the ALCHEMI module with two different POE – the currently used Gen 3 with its optimized module height (●, blue dashed line) and the temperature adapted lens (TAFL) Gen 4 (●, magenta line) with a slightly different module height. For comparability, the same Gen 1 SOE is used in all cases. The temperature behaviour of the Fullsun's module is shown in black for reference. The bullets correspond to simulated cases, whereas the spline lines are guides for the eye. Note that the blue and the black lines here correspond to Figure 5 (b).

SUMMARY

The ALCHEMI consortium has made significant strides to achieve the project goals. The Gen 1 Fullsun module design has been reconfigured to achieve the desired 1000 sun operation. State of the art cells have been procured from three separate sources, permitting comparison of these cells in the new module design. The cells have been incorporated into a receiver designed to populate the module PCB backplane, and over 6,000 receiver have been fabricated and tested and binned. Assembly of 10 modules is underway and will be complete early in 2019, with modules to be tested on-sun in Cyprus from mid 2019. It is expected that this on-sun testing will take place for a minimum of six months, and comparison of ALCHEMI module performance with Gen 1 modules and other types of PV co-located on the same tracker and in the same location. Results of this on sun testing will be reported elsewhere, when sufficient data has been collected

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