Analysis of CPV research findings (D16)

This report has been produced for the Cyprus Research Promotion Foundation in fulfilment of deliverable number D16 of the project “Advanced Photovoltaics Research and Testing for Improved Technologies”, grant number ΑΝΑΒΑΘΜΙΣΗ/ΠΑΓΙΟ/0308/21.

Contents

1. Introduction
2. Outdoor testing
   2.1 Spectrally tuned multi-junction cells with secondary optics
   2.2 70 X geometric concentration CPV system
3. Indoor testing
   3.1 Spectrally tuned multi-junction cells
4. Summary

1. Introduction

D16 is a deliverable of Work Package 7 which targets the development of advanced testing and rating procedures over and above those included in the standard for CPV. The purpose of this is to obtain a greater understanding of the strengths and weaknesses of the current standard IEC 62108 and thus investigate whether there is a need to adopt such advanced procedures in future type approval specifications. In D16, we present a report on the analysis of the data generated through the advanced testing procedures carried out at the laboratory and outdoor test site.

2. Outdoor testing

2.1 Spectrally tuned multi-junction cells with secondary optics

The spectral content of sunlight over a year varies with location on earth with the result that a similar cell will not necessarily deliver the same energy yield from place to place even if the irradiation resources are similar. Using spectrally ‘tuned’ solar cells designed and fabricated for a given location could maximize annual energy yields. Spectral tuning can be achieved with the inclusion of quantum wells in the structure of triple junction devices. Spectrally tuned quantum well solar cells were produced for highest energy yield in Cyprus. To investigate the advantages of using spectrally tuned cells over conventional designs, a side-by-side comparison of the output of different cells operating under identical conditions was conducted. Figure 1 shows the normalized short-circuit current of both, conventional and spectrally-tuned
cells.

![Normalized short-circuit current vs. Local time](image)

**Figure 1:** Results of the side-by-side measurements of the different cell designs. The conventional design (shown in red) displays a stronger drop in normalized current late and early in the day.

Normalized short-circuit current of the quantum well solar cells is much higher than the equivalent of the conventional triple junction device. Furthermore, the short-circuit current of the quantum well remains the same during the day while the conventional design displays a large drop late and early in the day.

For investigation of the performance of the cells normalized power output was investigated against time. Maximum power results for both types of cells have been performed and showed clearly the superiority of the spectrally tuned quantum well solar cells over the conventional triple junction devices. Power output for cells suited to spectrum is at least 0.5 W higher than the conventional cell’s power. For all the data, best measurements were taken during midday due to clearest sky conditions.

Direct normal irradiance (DNI) was calculated by SMART’s model, at five minutes interval and at the preferable conditions of 'clear-sky’. Several DNI’s were calculated and the simulated spectrum that produced the best fit to onsite measurements of DNI was used to generate energy harvest predictions for spectrally tuned quantum well solar cells. This process involves the calculation of an estimated energy yield for the cells. Spectral resource and other parameters modeled by SMART’s are then compared with the real performance data taken at the University of Cyprus as shown in Figure 2. An underestimation of the real outdoor data it is apparent from the comparison of the modeled and measured normalized short circuit current against atmospheric depth. Deviations between the data are maybe due to the fact that the optics were not sufficiently model by SMART’s. The shape of the measured curve suggests that the cell used is bottom junction limited. Infrared irradiation loss in the modeled data is presenting due to not efficiently modeling of the optics used in the cell design strongly affecting the current at higher air mass where infrared irradiation is higher. In the middle of the day the infrared irradiation is smaller and the optical losses eliminated. Consequently modeled results approximate well with measured data as it is apparent from Figure 2.
Impact of Compound Parabolic Concentrator

The use of second stage optical elements in concentrator modules is potentially another way to increase cell efficiency through correction of aberrations of the primary optics and to increase flux concentration levels at the cell. In order to investigate the impact of secondary optics on the electrical parameters of the cell, a side-by-side measurement of identical cells with and without CPC has been performed. Comparison of the performance of the modules against the time of day is shown in Figure 3.

Figure 3: Comparison between the performance of modules with a secondary (red), and without (blue) against the time of day. The cell under test is a spectrally tuned quantum well solar cell.
Deliverable Report D16

Normalized maximum power of both designs is approximately the same. For further investigation of the results and explanation of the behavior of maximum power, normalized short-circuit current and open circuit voltage were plotted against time of day. Both current and power were performed as a function of DNI to have accurate comparison between the modules. Normalized current results showed higher currents for the module with secondary optics indicating better optical efficiency and consequently higher concentration levels. Investigation of the open circuit voltage of the module with Compound Parabolic Concentrators it is around 0.05 lower that the module with typical Fresnel configuration. Due to higher concentration levels within the modules with secondary optics the open circuit voltage is expecting to drop at lower values. This is an indication of the temperature difference between the two modules due to different concentration levels. Likewise fill factor results indicate the higher operating temperature of the module with CPC since it has lower values.

Conclusions

Detailed outdoor analysis of the electrical characteristics of spectrally tuned solar cells has indicated the potential advantages that such approach has. Highest output power and short circuit current showed clear improvement in the performance of the new technology cells. Better energy yield of the spectrally tuned cells can be interpreted as an indication that the cells are better suited to the range of spectra that they have been exposed to.

From the investigation of the performance of the improved optical arrangement with the Compound Parabolic Concentrator, a number of advantages of the new configuration have arisen. Providing higher flux concentration in the target area, higher currents of the triple junction cell have been obtained. Higher currents lead to the superiority of the new design against typical Fresnel configuration especially in the middle of the day where infrared losses are eliminated. For the reduction of optical losses, secondary optic design should improve in order to provide homogeneous spread of light in the surface of the cell at larger acceptance angles.

2.2 70 X geometric concentration CPV system

The CPV collector that has been studied in this work represents a low-concentration (70 X geometric concentration), mono-crystalline silicon cell design that uses Fresnel lenses and no secondary optic. The unit has a nominal output of 330 Wp at 850 Wm⁻² direct normal irradiation (DNI), 25 °C cell temperature and an average flux concentration of approximately 50 suns. The system employs mono-crystalline silicon cells adapted for use under concentrated sunlight, with operating efficiencies of approximately 19% under standard test conditions.

Current-voltage (I-V) characterizations of modules were performed every 1-5 minutes and key performance indicators alongside environmental and irradiance data were recorded. The performance of the system was monitored for three years. Only occasional cleaning was performed, which was done intentionally to examine the impact of soiling on the system output. The CPV system was left open-circuited between measurements. The power output of the system was measured by extracting the maximum power point (mpp) of each I-V characteristic, which avoided the need to account for the effect of an mpp tracker. The long-term testing of the CPV module provided valuable information on the performance ratio, the tracker performance, the operating temperatures and the optical efficiency.
The **performance ratio** (PR) was used as an indicator for the long-term operating efficiency of the system. The PR was calculated by dividing the long-term operating efficiency by the system efficiency at STC (13.5%). The results of the PR analysis are shown in Fig. 4.

![Figure 4: Cumulative energy yield plotted against the cumulative DNI resource showing a drop in output over a specific period during which the tracker malfunctioned.](image)

The efficiency of the system was determined to be 8.7% over the long term, corresponding to an annual PR of 0.64. The system was left intentionally uncleaned for the period in question and this lowered the PR accordingly. Operating efficiencies recorded at low ambient temperatures and when the lenses were clean reached 11.5% corresponding to a PR of 0.85.

Concerning **tracker performance**, problems were manifested in two ways. Firstly, extended exposure to the elements combined with working stress brought about a fracture in a plastic bearing holding the tracker in place. This resulted in a reduction of the energy yield of the collector by up to 50% as shown by the gradient of the curve in Fig. 4. With this particular fault the system was able to operate at maximum for some parts of the day, only failing to track the sun when the faulty section of the bearing was loaded (see Fig. 5, left). The Isc (shown in blue) which was sued as an indicator of the output of the collector deviated from the output expected by the modeled acceptance of the unit. By replacing the faulty bearing the tracker functioned without problems for 1.5 years.
The calculated acceptance curve shows the anticipated output profile if light was accepted by the system over the day without interference. The peaks on either side of the graph result from off axis light reflected from the side walls onto the cells.

The second tracking problem involved the degradation of the transparent cover of the photodiodes used as a pointing sensor (a four-quadrant arrangement of sensors was used). Over time the deposition of minerals and dust around the sensor head introduced variations in the transmissivity of each sensor cover increasing the tracking error at lower DNI levels. The right hand plot of Fig. 5 illustrates the effect, reducing the tracking efficiency under lower irradiance conditions. This was corrected through a combination of cleaning the sensor cover and performing software compensation.

The operating cell temperatures were also investigated as part of this work. Cell temperatures were determined using back-of-module temperature measurements. A 1-diode model of the system to predict I-V curves under certain temperatures was used to convert back-of-module temperature measurements to cell temperatures. It was found that a temperature difference of about 10 °C existed between the cell and the back of the module, with no considerable thermal lag under varying conditions.

**Figure 5:** Two types of observed tracking faults: (left) mechanical and (right) sensor cover soiling. The calculated acceptance curve shows the anticipated output profile if light was accepted by the system over the day without interference. The peaks on either side of the graph result from off axis light reflected from the side walls onto the cells.

**Figure 6:** Surface map of the modelled cell temperature above ambient as a function of wind speed and current.
The first result from this work was that the operating cell temperatures measured were similar to the nominal operating cell temperatures (NOCT) of flat plate PV modules. The results also showed that even low wind speeds of 1 m/s can reduce the temperature of the cells by up to 5 degrees and that any subsequent rise in wind has a diminishing effect up to the measured influence of 10 °C. For summer months in Cyprus, this implies peak operating temperatures of about 65-70 °C, equating to a 15-20% drop in power output for crystalline Silicon cell systems, compared with the rated performance.

![Figure 7: Isc output normalized to 1000 W/m² DNI, showing a decrease in output over time due to lens soiling.](image)

The most significant source of loss of optical efficiency was identified as the effects of dirt accumulation on the front surface of the Fresnel optics. During a 6-week period in summer, the absence of rain allowed the daily rate of output degradation due to soiling to be studied as shown in Fig. 7. The results showed a daily decrease in output of 0.2%. After nearly 1.5 years of exposure, the system was cleaned and an immediate increase in the system output of about 33% was recorded. It should be noted that once cleaned and properly oriented the system output returned to the initial levels recorded immediately after installation.

3. Indoor testing

3.1 Spectrally tuned multi-junction cells

**EL data**

All samples are InGaP/InGaAs/Ge triple junction devices with In\(_x\)Ga\(_{1-x}\)As QWs incorporated within the InGaAs middle junction. The incorporation of strain balanced InGaAs QWs with higher proportion of Indium into the intrinsic region of InGaAs middle junction has been shown to affect the emission wavelength and increase the short-circuit current of QW solar cells. Non-destructive techniques such as external quantum efficiency (EQE), Photoluminescence (PL) and electroluminescence (EL) have been used to characterize the innovative devices. Room-temperature EL spectra was performed at current of 20mA for all investigated samples. Each spectrum is dominated by a sharp emission peak in the spectral region of the barrier materials and QWs as shown in Figure 8.
In order to investigate carrier injection mechanisms, examination of the current dependence of EL has been performed (see Figure 9).

EL spectra were recorded under different current intensities varied between 5 mA to 100 mA for sample 5.8 (Fig. 9). Increasing current causes generation of more carriers in the bands which recombine through radiative and non-radiative recombination mechanisms. No significant shift in the EL peak position against current can be observed in the measurements indicating that band filling effects and screening of the quantum confined Stark effect (QCSE) are not of major influence in the investigated samples. Saturation of peaks in all samples except sample 7.5 occurs at the same current (80mA) while saturation in sample 7.5 occurs at 40mA indicating the existence of narrower wells.
For the investigation of the radiative recombination mechanisms involved in PL measurements the integrated optical power was plotted against the excitation power on a logarithmic scale. The logarithmic plot for the sample is around 1.25 indicating that bimolecular recombination processes are involved.

In order to investigate the effect of temperature on the emission from the samples, temperature dependent EL of samples was measured for a broad range of temperatures.

![Figure 10: Temperature dependence of EL for sample 5.8.](image_url)

As shown in Figure 10 with temperature increasing, EL peaks move to longer wavelengths (redshift) and to lower intensity values. It is well known that the radiative carrier recombination is stronger at lower temperatures whereas at higher temperatures carrier recombination is dominated by non radiative recombination. Also thermal escape of carriers is strongly enhanced by increasing the temperature of the sample. Therefore the carriers are not contributing to the radiative recombination and the emission is expected to decrease at higher temperatures as a result, which is in agreement with the actual results taken. Redshift of the spectra is attributed to band gap shrinkage of QWs with increasing temperature. Redshift is the cause of splitting of peak D into two smaller peaks D$_1$ and D$_2$. Splitting of the peak D to two smaller peaks appears around 41 ºC and is related to the existence of different amounts of Indium in peak D around 924 nm at 5.8 sample.

**EQE measurements**

For external quantum efficiency measurements cell photocurrent was recorded using standard lock-in techniques and EQE was derived by comparing the cell photocurrent with that from a silicon calibrated photodiode. Figure 11 displays the EQE results of the middle junction InGaAs for a selection of cells in order to demonstrate the effect of the presence and number of QWs on EQE signal.
Figure 11: Room temperature EQE for all samples under investigation

Clearly the presence of QWs has extended the EQE response to longer wavelengths as can be seen by the peaks above 887 nm which is the band gap of the barrier InGaAs material. With the EQE method, indication of QWs presence is observed only in the region with the largest number of wells, which correspond to peak D. The EQE results are in agreement with the actual results taken with the EL method. The highest peak intensity -both in EQE and EL- is in the region of the largest number of QWs (peak D). Agreement between results is presented also in the peak wavelengths with the EQE peak wavelengths existing at the same wavelengths with EQE peaks.

PL measurements

Excitation dependent PL measurements have also been performed in order to further investigate carrier injection mechanisms. Excitation dependent PL has been performed at 300 K (fig. 12, left) and at 15 K (Fig. 12, right).

Figure 12: Excitation dependence of the PL spectra at 300 K (left) and at 15 K (right).
Absence of significant shift in the PL peak position as a function of excitation power can be observed in both graphs indicating the absence of band filling effects. The PL spectra obtained at room temperature (Figure 12, left) are in agreement with the EL spectra shown in Figure 9. The spectra at 15 K are dominated by radiative recombination and have differences with the spectra recorded at room temperature. In Figure 12 (left) it is clearly shown that the PL peak against excitation power is moving towards higher wavelengths (redshift). Normally with increasing excitation power the peak is expected to exhibit blueshift due to band filling effects. In our case the increased excitation power at low temperatures causes heating of the sample and therefore redshift. Redshift of the PL emission is observed at very low excitation levels (below 1 mW) indicating that the heating is significant even at low light excitation. Another important observation is the decrease of the PL peak and therefore reduction of the integrated PL emission at excitation power of 30 mW. It is well known that, at low temperature, the increase of the excitation density results in PL saturation.

For the investigation of the radiative recombination mechanisms involved in PL measurements the integrated optical power was plotted against the excitation power on a logarithmic scale. Linear fitting of the curve showed that the resulting slope is 1.29 indicating the existence of bimolecular recombination with losses due to non-radiative recombination.

In order to investigate the effect of temperature on the emission of the samples, temperature dependent PL measurements have been carried out in a broad range of temperatures. PL measurements were investigated at temperatures between 15-300 K as shown in Figure 13.

**Figure 13: Temperature dependent PL spectra between 15-300 K.**

At lower temperatures the luminescence efficiency can be considerably higher than at room temperature as the ratio of the radiative to non-radiative rate is greatly increased. Figure 13 shows that the PL signal at 15 K is roughly 256 times higher than the signal at 300 K. PL peak energy is redshifted with increasing temperature due to the temperature induced band-gap shrinkage. The PL peak energy redshifts by 79.9 meV for temperatures in the range 15-300 K. At temperatures above 100 K quenching is higher compared to temperatures below 100 K. Different temperature quenching is related to the amount of non-radiative recombination centers. The rate of band-gap shrinkage indicates the presence of more alternative paths of non-radiative recombination at temperatures between 150-300 K.
Finally a comparison between EL and PL was undertaken at room temperature. The results showed excellent agreement between both methods as shown in Figure 14.

Conclusions

EL and PL measurements were carried out to investigate triple-junction InGaP/InGaAs/Ge devices with InGaAs QWs in the emission range from 600 nm to 950 nm. The work provided an insight into radiative recombination processes that occur in wells at high and low temperatures.

Excitation dependent EL and PL measurements at room temperature showed the absence of band filling effects since no significant blueshift was observed at higher injection currents. Excitation dependent data from both methods showed that bimolecular recombination is dominant at room temperature indicating the presence of bound electron-hole recombination.

4. Summary

In this report we present the analysis of indoor and outdoor performance of CPV cells, modules and systems undergoing advanced testing procedures, beyond those contained in IEC 62108. The 70 X geometric concentration CPV system, was studied in this work package. The long-term testing of the CPV module provided valuable information on the performance ratio, the tracker performance, the operating temperatures and the optical efficiency. Also, advanced evaluation measurements such as EL, PL and EQE measurements from novel III-V multi-junction solar cells are presented particularly from spectrally tuned multi-junction cells with and without secondary optics. The work provided an insight into radiative recombination processes that occur in wells at high and low temperatures. Detailed outdoor analysis of the electrical characteristics of spectrally tuned solar cells has indicated the potential advantages that such approach has. Better energy yield of the spectrally tuned cells can be interpreted as an indication that the cells are better suited to the range of spectra that they have been exposed to.