

# EVALUATION OF COMPETING TRIPLE JUNCTION CONCENTRATOR CELLS BY ELECTROLUMINESCENCE

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## ABSTRACT

Electroluminescence (EL) can provide a valuable insight into the performance of individual junctions in a triple junction cell designed for use in high concentration photovoltaic (HCPV) applications. It has the potential to be used in quality control in cell production as well as providing specific information about the performance of the cell's emitter and metallisation scheme. This paper presents an EL examination of triple junction photovoltaic cells from four commercial vendors of (Al)InGaP/(In)GaAs/Ge based concentrator cells and analyses their suitability for use in a HCPV system.

## INTRODUCTION

The highest efficiency solar cells (>40%) that are available in the lab today are based on triple junction cells either grown on a Ge-substrate [1] or are so-called inverted metamorphic (IMM) cells grown on a GaAs substrate [2] which is subsequently sacrificed and in-principle could be re-used [3]. On the other hand commercially available cells have an upper limit on efficiency of >38% [4]. These multi-junction (MJ) cells are complex in nature and difficult to fully characterize in a non-destructive fashion.

Electroluminescence (EL) offers a straight forward, non-destructive method of evaluating the performance of MJ cells. Spatial imaging can readily reveal information about defects in the epitaxial structure or metallic contact grid pattern, while line-scans between the top contact grid pattern reveal the efficacy of the design of the emitter contact layer.

Currently the supply of MJ cells for HCPV applications is dominated by vendors, Spectrolab, Emcore and Azur Space, all of whom have an impressive track record in supplying cells for space applications. The huge potential of the HCPV market has attracted a number of other potential vendors into the market. Several of these, Solapoint, Arima Eco, VPEC, IQE, etc...are looking to deploy their optoelectronic expertise into a new commercial arena or like Cyrium, Quantasol or SolarJunction exploit new concepts or materials to increase the efficiency of MJ solar cells.

Here we present an EL examination of triple junction photovoltaic cells from four of these commercial vendors

of (Al)InGaP/(In)GaAs/Ge based concentrator cells and analyse their suitability for use in a HCPV system.

## TRIPLE JUNCTION CELLS

The detail of the epitaxial structures of the MJ cells remains proprietary information to each supplier. However, from vendor supplied datasheets we know that all of the cells are of the type (Al)GaInP/(In)GaAs/Ge. A schematic of the epitaxial structure of the cells is shown in Figure 1.

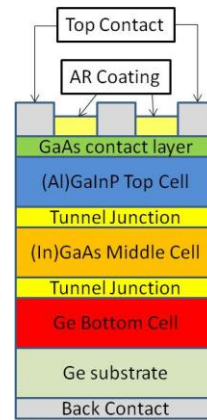


Figure 1: Schematic of the Epitaxial Structure of the triple junction cells.

In Table 1 we show details of the cell areas and nominal efficiency for each of the cells examined in this study.

Vendor	Cell size (mm)	Active Area (mm <sup>2</sup> )	Nominal Efficiency (%)
V1	4.97 x 4.11	16.4	36.1(~300x)
V2	5.5 x 6.5	30.25	37.19(~180x)
V3	5.5 x 6.7	30.25	35.8 (170x)
V4	5.8 x 6.8	33.64	37.1 (170x)

Table 1: Cell dimensions, active area and specified efficiency for the cells from the four vendors.

## EXPERIMENTAL

The MJ cells under investigation were mounted onto an Aluminium core PCB similar to those used for the mounting of HBLed chips which potentially offer

excellent thermal management of the PV cell, especially under high concentration. All the cells were attached to the PCB using a silver loaded epoxy and front contacts made to the devices using gold wire bonds. The cell assembly is then mounted in an Aluminium mechanical test fixture which is used for both the EL and flash test measurements.

Driving the cells into forward bias makes them behave just like LEDs and the EL generated at each junction can be imaged using an appropriate CCD camera. The design of the MJ cells studied here means that the generated photons have wavelengths of ~680nm (top cell), ~880nm (middle cell) and around 1700nm (bottom cell). The direct nature of the bandgaps of the top (InGaP) and middle ((In)GaAs) cells means that the EL should be very strong whereas the third, Ge, junction is indirect and produces weak EL in the far-infrared part of the spectrum. To image all three cells would mean having to use both a Si-based CCD camera (top and middle cells) and an InGaAs based camera for the far-infrared emitted from the bottom cell. Here, we have employed only a Si-based CCD allowing us, with the use of appropriate filters, to individually monitor the PL from the top and middle cells.

Images from the CCD camera are then analyzed using Labview to generate false colour images of the electroluminescence intensity and intensity cross sections between grid fingers, for example.

In addition to EL measurements we have also examined the cells under conditions meant to simulate illumination under concentrated sunlight. These measurements were carried out at ambient temperature using a so-called flash system. The cells were flashed using a commercial photo-flasher (Linkstar LF750A). The flashbulb is filled with Xenon to try and match the UV end of the solar spectrum but any spectral mismatch will, of course, influence the determined maximum power point, fill factor and short circuit current and thus the calculated efficiency. Whilst the absolute efficiencies are in some error this is not likely to be the case when comparing relative measurements.

## MEASUREMENTS and DISCUSSION

In Figure 2 we show the spectrally resolved EL from typical cells from all vendors.

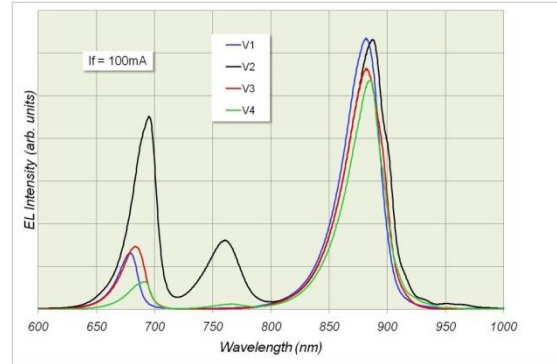


Figure 2: Spectrally resolved EL from the top and middle cells of a MJ cell.

The spectra from each vendor has common features indicative of the general design rule for a triple junction PV cell; A top cell peak ~680nm and a middle cell peak ~880nm. What's interesting here is that the EL spectrum from the two vendors V2 and V4 shows clear evidence of a peak at ~760nm. No such feature is evident in the other two spectra. Without a detailed knowledge of the epitaxial structure of the MJ cells we can only speculate on the origin of this emission. Its wavelength would be consistent with emission from a bulk (AlGa)As layer with an Al mole fraction of ~0.15. It is quite possible that a layer of this composition has been introduced as part of the tunnel junction (TJ) structure between the top and middle cells in order to try and maximize the p-type doping in this structure. Whilst, we see no evidence that inserting a layer with this composition as part of the TJ has any detrimental effect on the I-V characteristics of the device, even up to >500x, it is clearly undesirable from an efficiency standpoint since light will clearly be absorbed at this intermediate wavelength which will inevitably impact on the overall efficiency of the cell.

The small differences in the bandgap of the (InGa)P used in the top cell of these MJ cells almost certainly reflects differences in the MOCVD growth conditions used by the different vendors. These differences in growth conditions manifest themselves in different degrees of ordering of the (InGa)P alloy [5] which in turn results in small differences in the measured energy gap.

One of the powerful features of EL is its ability to give spatial information about the distribution of current between the grid fingers of the top contact. This can be monitored as a function of increasing concentration where one of the limiting factors in performance is due to inefficient collection of the large emitter currents due to the resistance of the top n++ GaAs contact layer. Imaging the EL from the top cell alone is sufficient to observe this effect as it is anticipated that lower junctions should be less affected by current spreading (Figure 3).

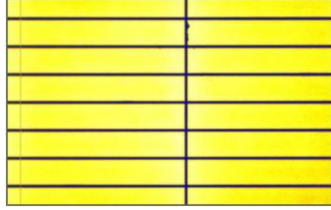


Figure 3: Spatially resolved EL spectrum from the middle (InGa)As cell of the triple junction cell from vendor V3. The cell is in forward bias at a current of 320mA.

In addition to highlighting these lateral resistance effects the spatially resolved EL will also provide information about macroscopic effects such as damaged or broken contact grid fingers and microscopic material defects that will most likely show themselves as dark spots in the EL image as they are acting as non-radiative centres.

In Figures 4 and 5 we show an example of the effect of some of these gross defects.

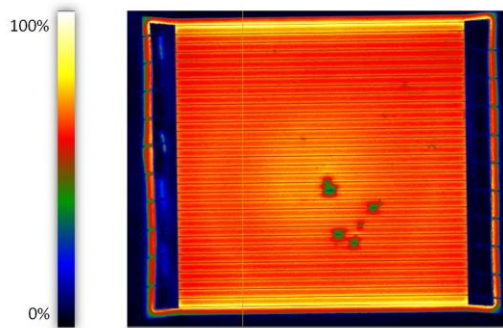


Figure 4: Spatial EL image of a cell from vendor V2 taken at a forward current of 100mA.

At this drive current of 100mA it is clear (Figure 4) that the colour of the image is quite uniform indicating an uniform distribution in both current and voltage between the grid fingers. Obvious exceptions to this are the defect areas just off-centre right of the image. These lower current areas surround points where the grid fingers have been damaged. This damage to the grid fingers was an exception amongst the cells examined, with most contact fingers showing no defects.

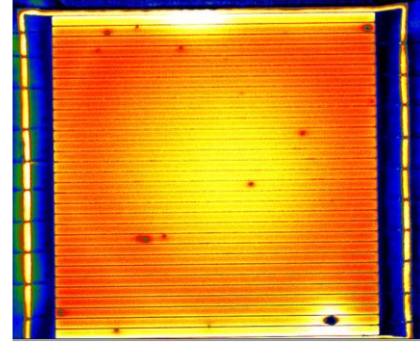


Figure 5: Spatial EL image of the top cell of a MJ PV-cell from vendor V4 taken at a forward current of 100mA.

Figure 5 shows a spatial EL profile from vendor V4 which is not as uniform as that shown in Figure 4. Both figures were taken using a drive current of 100mA. From this visual comparison it is clear that the current spreading and hence resistance of this device is not as good as that of V2. Also illustrated is the ability of EL to reveal dark spots (or defects) in the epitaxial layers that indicate less than ideal quality of the epitaxial layers – in this case, the InGaP top cell.

Since we intend to employ commercially available MJ cells in our HCPV system it is important that we monitor the performance of available cells as a function of concentration (or its equivalent forward bias current) and select the cells best matched to our intended exposure conditions (>500x). In order to facilitate selection of cells we have performed EL measurements as a function of forward bias current and combined these observations with the flash measurements outlined above.

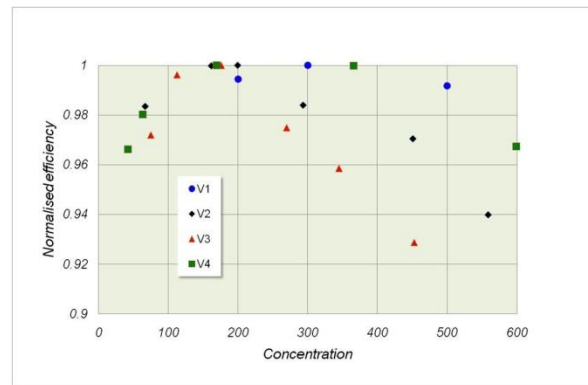


Figure 6: Normalised cell efficiencies as a function of concentration.

In Figure 6 we show the normalised cell efficiencies as a function of the concentration factor. Increasing the concentration increases the photocurrent generated and

so increases the current density. This in turn increases the potential drop due to series resistance in the cell. This can be a particular problem in the emitter layer where lateral current densities are high. Good design of metallisation patterns and optimization of emitter doping levels and thickness are essential to prevent an early decrease in the efficiency of the MJ cell as the concentration increases.

From Figure 6 it's clear that the cell designs favoured by vendors V1 and V4 have the smaller series resistance and make these cells far more suitable for a HCPV application unlike V2 and V3 which both have maximum efficiencies ~180x. EL imaging of V3-cells illustrates nicely what is happening as the forward current is increased in the cells as we show below.

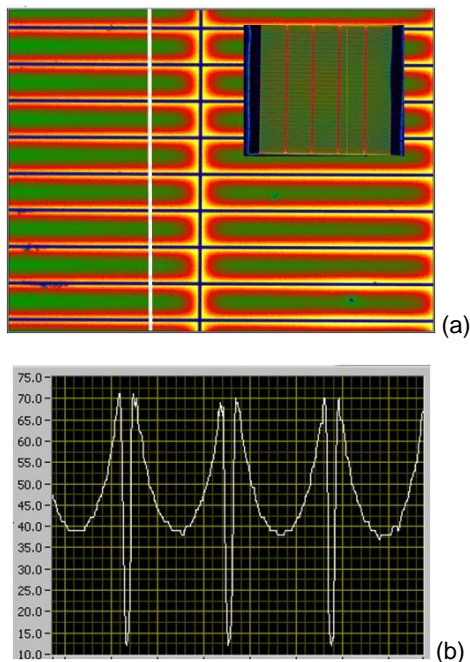
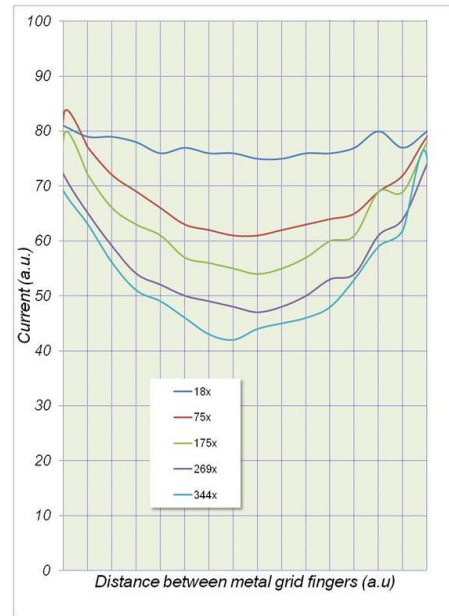


Figure 7: (a) Higher resolution spatial EL map of a cell from V3 at a forward bias current of 320mA (75x). The top contact metal configuration is shown in the inset. (b) a line scan (white line in (a)) showing the variation in current between the top contact grid fingers.

A powerful way of looking at the efficacy of a grid pattern and contact layer epitaxial design is to study line-scans of the EL intensity between the grid fingers as a function of forward bias current (concentration). This is what's shown in Figure 8, where we have plotted the profile of the EL intensity (or equivalently the forward current distribution) between the grid fingers of a cell from vendor V3. It's clear from this plot that increasing concentration results in an increase in the resistive contribution of the emitter layer which shows itself as a significant lowering of the current between the grid fingers.



Figures 8: Normalised EL intensity measured between the grid fingers of a cell from vendor V3 as a function of forward bias current which has been converted into an equivalent concentration factor.

## SUMMARY

We have compared, under conditions of high concentration, the performance of (InGa)P/(InGa)As/Ge triple junction cells currently available from four commercial vendors. We find that two of these cells are best suited for use in HCPV systems where concentration levels are typically >500x. EL has been shown to be an extremely effective tool in not only screening out cells with gross defects but in also revealing the effectiveness of the cell's emitter doping and metallisation scheme.

## REFERENCES

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