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# Comparison of Various InGaAs-based Solar Cells for Concentrated Photovoltaics Applications.

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**Abstract.** InGaAs lattice matched to InP is a promising material for bottom sub-cell in a 4-junction solar cell designed for concentrated photovoltaics applications. Here we compare the performances of two structures that could replace standard monolithic InGaAs homojunction. The first one is a stand-alone solar cell realized via epitaxial lift-off (ELO) process on a flexible substrate. The second one is a heterojunction solar cell, kept on its parent InP substrate, composed of an InP emitter and an InGaAs absorber. A third structure made of an homojunction InGaAs solar cell on an InP substrate is used as reference. Under one sun illumination the heterojunction solar cell shows the highest  $V_{OC}$  (383 mV) and fill factor. Nevertheless, when performing under concentrated sunlight the structure is limited by a lower  $V_{OC}$  increase rate and a high series resistance compared to the ELO cell. Indeed, ELO cell shows a lower  $V_{OC}$  (353 mV) than the two other structures under one sun illumination but, when performing under concentration, ELO cell recovers  $V_{OC}$  and shows a lower impact of series resistance. Therefore, both ELO and heterojunction solar cell show interesting and complementary behaviors that could be interesting to associate in an ELO-heterojunction solar cell.

## INTRODUCTION

Optimization of multi-junction solar cells (MJSC) performance while keeping a low fabrication cost would allow to decrease the overall cost of the electric energy produced in concentrator photovoltaic (CPV) power plants. High performance MJSC reaching an efficiency of 46% under 508 has been achieved thanks to the association of InP-(InGaAs, InGaAsP) and GaAs-(GaAs, InGaP) based III-V semiconductors<sup>1</sup>. However, many experimental efforts can still be done to reach highest efficiencies with such a combination of different band gaps materials according to theoretical studies<sup>2</sup>. Therefore, optimization of each subcell performance under concentration is still needed, especially for the bottom InGaAs one. Indeed, its position close to the back contact allows to easily implement novel solar cell schemes.

In this effort, the fabrication of the bottom subcell over a back mirror, leading to photon recycling in this subcell<sup>3-5</sup>, could improve the MJSC performances<sup>6</sup>. This was widely studied specifically on GaAs mono-junction solar cells which represent so far the highest efficiency ever realized for a mono-junction solar cell<sup>7-9</sup>. In a MJSC architecture, the simplest way to realize the photon confinement is to use a backside mirror as a backside contact leading to photon recycling in the bottom subcell.

A different way to increase bottom sub-cell performances could be to replace the standard InGaAs emitter by an InP emitter over the InGaAs base. As demonstrated by Ochoa et al.<sup>10</sup> such an heterojunction structure should allow to decrease recombination at the edges of the solar cell therefore leading to a small increase of the open circuit voltage ( $V_{OC}$ ). Ochoa et al. also showed that this effect should be more visible under 1 sun illumination and low concentration

factor than under high concentration illumination. Of course, both approaches can be realized simultaneously on a same structure, but we choose to focus on each structure separately.

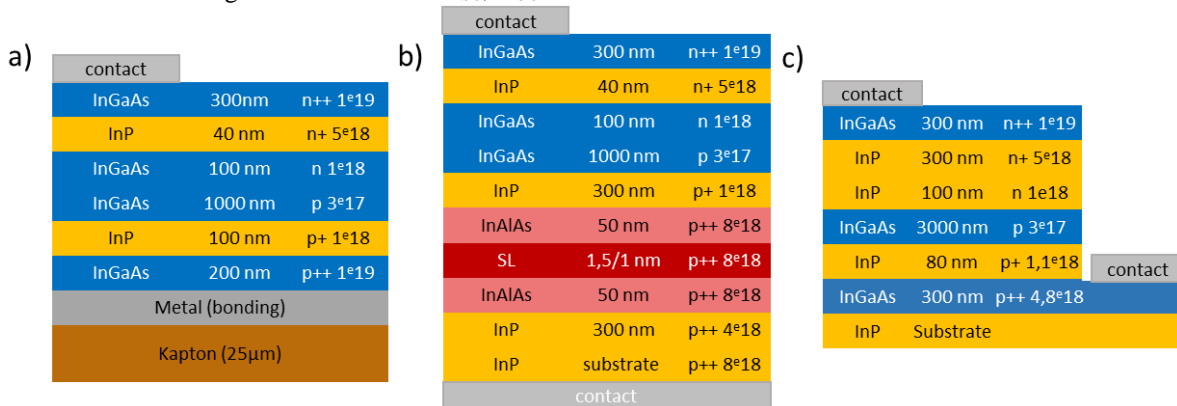
From these different assessments, we focus in this work on the behaviour of three different InGaAs-based structures designed to be incorporated in a final MJSC as a bottom subcell. The first structure is based on a standalone flexible InGaAs solar cell realized via Epitaxial Lift-Off (ELO) from an InP substrate. The second structure, used as a reference for the ELO solar cell, is a monolithic InGaAs solar cell. The last structure presented here is an InP/InGaAs heterojunction solar cell. Here we present the I-V measurements of these solar cells under one sun and concentrated illumination. In a first part, the three structures will be presented, then the results of these solar cells under one sun illumination will be described. Finally, the evolution of the  $V_{OC}$  and the Fill Factor (FF) of these 3 structures in function of the light concentration will be presented in order to assess which one is more suitable to operate under concentration.

## MATERIALS AND METHODS

This study focuses on three different structures all based on InGaAs absorber. The first structure consists in a flexible monocrystalline solar cell realized via ELO process. The fabrication consists in the report of the structure on a metallized flexible superstrate and the selective chemical etching of an AlAs/InAlAs superlattice as a sacrificial layer. This fabrication process leads to a standalone III-V solar cell over a metallic mirror (called ELO cell in the following, see Fig. 1a.). The second structure is a monolithic solar cell grown on the same AlAs/InAlAs superlattices but kept on the substrate (Monolithic/SL in the following, see Fig. 1b.) which is used as a reference for the ELO solar cell. These two structures were grown using solid-source Molecular Beam Epitaxy (ssMBE) and more details about the full fabrication process are presented in a previous work<sup>11</sup>. The last structure is a monolithic InP/InGaAs heterojunction (HJ) grown using MetalOrganic Chemical Vapour Deposition (MOCVD) on an InP substrate (denoted monolithic InP/InGaAs HJ in the following, see Fig. 1c.).

The different solar cells were fabricated by deposition of a Ni/Ge/Au/Ni/Au front contact grid, chemical etching of the contact layer and cell isolation using a wet chemical etching. The back contact of the ELO cell was made by deposition of Cr/Pt/Au and bonding on a metallized polyimide superstrate. The monolithic/SL solar cells were back contacted via blanket deposition of Ti/Au on the p+ InP substrate. The back contact of the InP/InGaAs cell was made by depositing Ti/Au on highly doped p+ InGaAs layer in a front side configuration. The size of the cells is 1x1 mm<sup>2</sup> for the ELO cell, 3.5x3.5 mm<sup>2</sup> for the monolithic/SL cell and both 1x1 mm<sup>2</sup> and 3.5x3.5 mm<sup>2</sup> for the InP/InGaAs one. The Figure 1 presents the final structures after fabrication.

One-sun illumination IV measurements were performed to evaluate the short-circuit current density ( $J_{SC}$ ), the  $V_{OC}$  and the FF. The  $J_{SC}$  was calculated considering the area losses from the bus bars and the grid lines. The light source used is a Newport Oriel Sol1A with AM 1.5D spectrum, and the setup was calibrated with an InGaAs solar cell. For the measurements under concentration, an AM 1.5D spectrum flash tester was used, with the device temperature controlled at 22°C during the measurements.  $J_{SC}$ ,  $V_{OC}$  and FF were measured between ~20 suns and ~200 suns.



**FIGURE 1.** Final structures, after fabrication, of the three different kinds of solar cells studied: a) ELO cell, b) Monolithic/SL cell and c) InP/InGaAs cell

## RESULTS & DISCUSSIONS

### One-Sun I-V

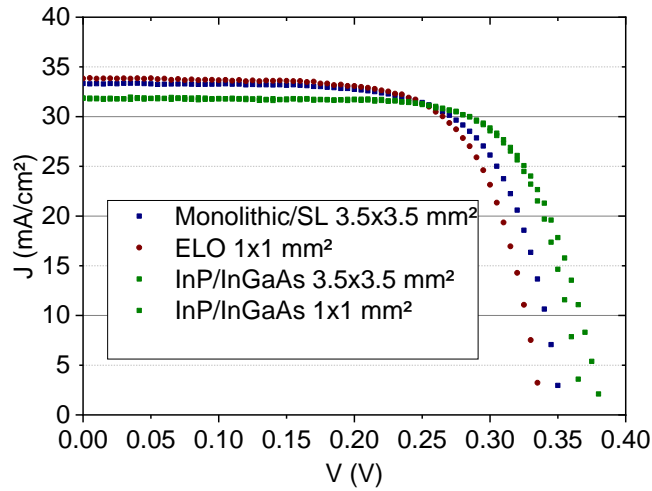


FIGURE 2. J-V of the various InGaAs solar cell included in the study

TABLE 1. InGaAs solar cells performances at one sun (AM 1.5D)

Solar cell	$V_{oc}$ (mV)	$J_{sc}$ (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)
Monolithic/SL 3.5x3.5 mm <sup>2</sup>	353	33.2	69.9	8.19
ELO 1x1 mm <sup>2</sup>	339	33.8	69.4	7.95
InP/InGaAs 3.5x3.5 mm <sup>2</sup>	383	31.8	71.0	9.19
InP/InGaAs 1x1 mm <sup>2</sup>	369	31.9	73.3	9.17

Figure 2 depicts the J-C characteristics of the previously presented InGaAs solar cells and the table 1 shows the extracted values.

At first sight, we can see that the hetero-junction solar cell presents the highest performances especially for the  $V_{OC}$ . On the same structure, we can observe a slight decrease of 14 mV of the  $V_{OC}$  between the 3.5x3.5 mm<sup>2</sup> and the 1x1 mm<sup>2</sup>. This decrease has already been observed in various GaAs, InGaAs and multijunction solar cells when solar cell area is reduced<sup>12-15</sup>. This loss was linked to recombination at the edge of arsenide based III-V cell.

The ELO and monolithic/SL solar cell show respectively  $V_{OC}$  of 339 and 353 mV. This difference in  $V_{OC}$  could come from the smaller area of the ELO cell and/or defects formed during the harsher fabrication process of the ELO cell.

The HJ solar cell with a thicker InGaAs absorbing layer offers a higher volume for recombination which should lead to a lower  $V_{OC}$  but the beneficial effect of the InP emitter counterbalances this effect leading to the highest  $V_{OC}$  measured in this study.

The obtained  $J_{SC}$  in this study are lower than previously reported results of InGaAs solar cell<sup>16,17</sup>, but this value is consistent as no antireflection coating was used in our study.

We can also observe a slightly higher  $J_{SC}$  of 0.6 mA/cm<sup>2</sup> for the ELO cell compared to the monolithic/SL that could come from light trapping due to light reflection on the back metallic mirror. On the other hand, the  $J_{SC}$  of the InP/InGaAs cell is in the same range as the ELO one whereas the InGaAs absorbing layer used in the monolithic InP/InGaAs HJ cells is thicker compared to the two other ones.

Regarding the literature it appears that the  $J_{SC}$  is usually unaffected or slightly affected for GaAs and InGaP solar cell on a metallic mirror<sup>3,18,19</sup>. In our case the InGaAs absorbing layer for the ELO cell is thin and the light is partly absorbed so the metallic mirror could have a higher impact. In the case of the monolithic/SL solar cell the back contact can also act as a metallic mirror even if it is on the backside of the InP substrate as InP is not absorbing in the near IR range. In the case of the InP/InGaAs HJ solar cell there is no full back side metallic mirror, so no reflection is expected.

Also, the collection efficiency the carrier collection efficiency at the highly doped upper InP layer can strongly affect the final  $J_{SC}$ . Due to this different effect the final  $J_{SC}$  of the InP/InGaAs solar cell is lower than the other ones.

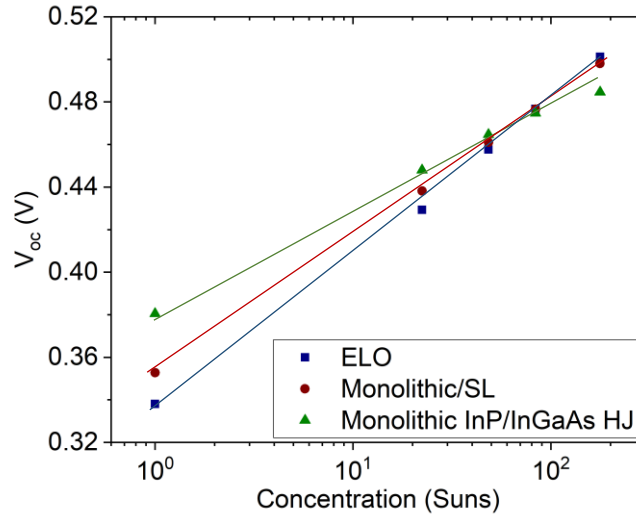
The monolithic InP/InGaAs HJ solar cell shows a slightly higher FF with an even higher FF when reducing the solar cell size from  $3.5 \times 3.5 \text{ mm}^2$  to  $1 \times 1 \text{ mm}^2$ . The lower value of FF observed on the ELO and monolithic/SL solar cell could come from a small decrease of the shunt resistance. This lower shunt resistance could arise from the harsher process used to fabricate these solar cells that could induce microscopic defect in the bulk of the material.

These different results show clearly that the InP/InGaAs solar cell gives higher performance than the two other cells under one sun illumination. However, this kind of cells is intended to be used under concentration in a MJSC architecture. In this scope, the evolution of  $V_{OC}$  and FF were recorded under concentrated illumination in order to clarify which structures offers the highest performances for concentrator photovoltaics application.

### Open Circuit Voltage Under Concentration

The studied solar cells aim to be implemented in an MJSC architecture where they will receive only the infrared portion of the solar spectrum. The concentration measurements were performed under a non-filtered standard direct solar spectrum. Therefore, the generated photocurrent is much higher than the generated photocurrent in a MJSC configuration for the same concentration. Consequently, it has been chosen to use concentration from 1 to 200 suns which correspond to an effective 800 suns concentration in the case of 4 junction solar cell. For concentration higher than 200 suns, all solar cells show performance degradation certainly due to the strong thermalization occurring when carriers are generated from high energy photon.

Evolution of the  $V_{OC}$  of the three different structures between 1 and 200 suns is depicted in Figure 2. The size of the InP/InGaAs solar cell is  $1 \times 1 \text{ mm}^2$  as the  $3.5 \times 3.5 \text{ mm}^2$  square showed too high series resistance when concentration rises above 50 suns and therefore were not measurable.



**FIGURE 3.** Evolution of the  $V_{OC}$  as a function of the concentration ratio (AM1.5D spectrum) of the three different kinds of solar cells studied: ELO cell ( $1 \times 1 \text{ mm}^2$ ), Monolithic/SL cell ( $3.5 \times 3.5 \text{ mm}^2$ ) and InP/InGaAs ( $1 \times 1 \text{ mm}^2$ ).

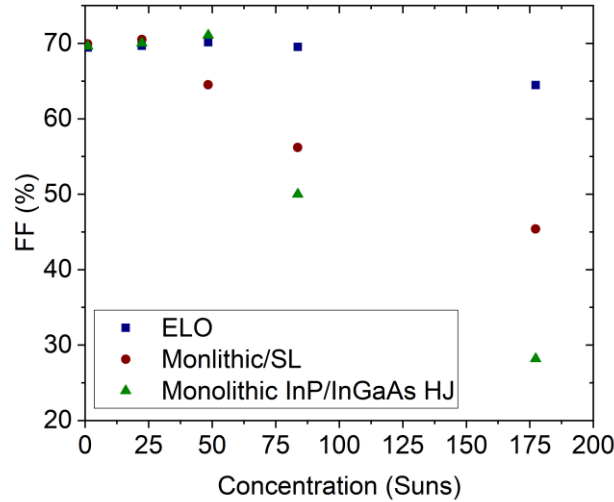
The  $V_{OC}$  of the three structures shows a logarithmic increase with the concentration factor, which is standard for solar cells. Only the InP/InGaAs measurements performed for concentration above 100 suns deviate from this logarithmic evolution. This deviation could be due to the high series resistance observed on this structure. This structure shows a lower increasing rate for  $V_{OC}$  compared to the other structures. This behaviour has already been predicted via simulation for heterojunction GaAs solar cell compared with homojunction GaAs solar cell <sup>20</sup>.

The ELO cell shows a higher increase trend in  $V_{OC}$  while increasing the concentration factor comparing to the other structures and especially comparing to the monolithic/SL cell. This higher trend might come from a saturation of recombination on the edge of the cells and/or in the defects created during fabrication of ELO solar cells. This phenomenon has already been observed on low area/perimeter ratio solar cell <sup>21</sup>. Above 100 suns, the ELO cell shows the highest  $V_{OC}$  probably enhanced by the photon recycling effects <sup>4,7,22-24</sup>. As the increase in concentration should not

enhance the photon recycling effect<sup>24</sup>, we can distinguish two main effects. First, the  $V_{oc}$  is mainly affected by defects recombination at low concentration even if photon recycling occurs, at higher concentration, the saturation of these defects could allow the photon recycling to be visible leading to a higher  $V_{oc}$  for the ELO solar cells. This result indicates that ELO solar cell with a metallic back contact and mirror are promising candidates to increase bottom subcell efficiency when operating under concentration.

### Fill Factor Under Concentration

Evolution of the FF as a function of the concentration ratio (between 1 and 200 suns) is depicted in the Figure 3.



**FIGURE 4:** Evolution of the FF in function of the concentration ratio (AM1.5D spectrum) of the three different kinds of solar cells studied: ELO cell (1x1 mm<sup>2</sup>), Monolithic/SL cell (3.5x3.5 mm<sup>2</sup>) and InP/InGaAs (1x1 mm<sup>2</sup>).

When increasing the concentration, the three different solar cell structures show a slight increase of the FF up to 50 X followed by a decrease. The InP/InGaAs solar cell shows the strongest decrease of FF with the increased concentration. This may be due to the lateral current conduction inside the InGaAs backside contact layer. Even if this layer is highly doped, the high electrical current crossing the device could lead to high Joule effect losses.

The second most affected solar cell structure is the monolithic/SL. Indeed, it is quite difficult to get a good contact on InP p+ substrate. Furthermore, the current needs to flow through the bulk InP which increases the series resistance. At the end, the ELO solar cell is the less impacted by the decrease of the FF. This enhanced behaviour is certainly due to the lower distance between the metallic contact and the active area and the easiness to contact the InGaAs p++ layer compared to the p+ InP layer. This result confirms the advantage to integrate ELO InGaAs subcell in a MJSC architecture as a bottom subcell.

## CONCLUSION

Three different structures of InGaAs solar cell have been studied in this work, an ELO solar cell fabricated over a metallized flexible substrate, a monolithic InGaAs solar cell and a monolithic InP/InGaAs heterojunction solar cell. The heterojunction solar cell shows highest performance under one sun illumination but seems to lose this advantage under concentration. This result is in accordance with simulation<sup>20</sup>. Optimization of the back contact using a full surface metal deposition may change this result.

On the other hand, ELO solar cells offer several advantages under concentration. First, it could allow photon confinement to happen inside the active structure via a backside metallic mirror. This effect allows to obtain higher  $V_{oc}$  under concentration for the ELO solar cell compared to the monolithic solar cells even if the 1 sun  $V_{oc}$  is lower for ELO solar cells. Furthermore, ELO solar cells allow a lower resistance for the backside electrical contact of the

solar cell. As a result, the FF of the ELO cell is less impacted when concentration ratio is increased than the FF of the two other types of structures.

Both heterojunction and ELO solar cell based on InGaAs absorbers do present advantages via increased performance. The strong impact of series resistance on the monolithic InP/InGaAs HJ cell could be corrected by structural optimization of the cell. This optimization would start by applying an ELO process on solar cell structure based on a InP/InGaAs heterojunction. In case of incorporation into a 4 junctions solar cell high energy photons will not reach the InGaAs solar cell, therefore the InGaAs subcell could be used at higher concentration (above 800 suns) without degradation. Also, InGaAs absorbing layer thickness would need to be tune in order to absorb the lower energy photons. Furthermore, using a high reflectivity backside contact could help decreasing the thickness of the InGaAs leading to higher  $V_{oc}$ .

Finally applying, the described advantages of ELO and heterojunction solar cell should be of great interest in order to obtain high efficiency bottom subcell for multijunction solar cell.

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