

ROADMAP TOWARDS EFFICIENCIES OVER 40% AT ULTRA-HIGH CONCENTRATIONS (> 1000 SUNS)

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ABSTRACT

High efficiency solar cells working under ultra-high concentrations (>1000X) have been shown to be a promising solution to decrease the cost of PV electricity, increase the efficiency and circumvent the material availability restrictions for massive PV penetration. A detailed analysis of the limitations of our current triple junction solar cell (36.2% at 700X), in the quest to maximize efficiency at 1000X, shows that the main improvements to tackle are: a) implementation of a high band gap tunnel junction; b) increase the band gap of the top cell; c) fine current matching tune; d) enhancement of the front contact process. This constitutes our roadmap to reach an efficiency over 41%.

INTRODUCTION

Record efficiencies of triple junction solar cells have been historically achieved within the range going from 300 to 500 suns: 40.8% at 326 X by NREL [1], 41.1% at 454 X by Fraunhofer Institute [2], 41.6% at 364 X by Spectrolab [3], 42.3% at 406 X by Spire [4] and 43.5% at around 400 suns by Solar Junction [5]. In most cases, the efficiency dramatically drops at concentrations of 1000 suns or higher. Alternatively, the operation at ultra-high concentrations (> 1000 suns) is expected to produce the following benefits:

- Cost reduction as consequence of a decrease of the solar cell impact on the final cost of the concentrator system [6].
- Increase of the raw material availability whose most severe limitation seems to be that of germanium substrates which is currently the preferred one for MJSCs [7]. Other materials used in the MJSC manufacturing such as TMGa for the MOVPE growth has increased recently its price as a consequence of the rapid penetration of LED backlighting modules in LCD TVs which absorbs most of the production of MOVPE consumables to date. Therefore, an increased concentration would relax this cost stress.
- Efficiency increase of the MJSCs with concentration as a result of the increase of its open circuit voltage [8] if its series resistance is kept low.

However, there are some concerns about going to higher concentrations than 500 X such as; 1) high concentrations usually lead to chromatic aberration in the optics; 2) such high concentrations raise doubts about cooling, series resistance and stability of MJSC; and 3) although the cost impact of the MJSCs is reduced, an increase on cost of

other elements such optics and tracking appears because of the need of a higher pointing accuracy. However, all these issues seem to be already properly faced [9].

Accordingly, the strategy of IES-UPM has been the design and manufacturing of III-V solar cells for operation at ultra-high concentrations. In fact, we have developed and manufactured a GaInP/GaAs dual-junction solar cell which exhibits an efficiency of 32.6% for a concentration range going from 499 to 1026 suns. This efficiency is the world record efficiency for a dual-junction solar cell [10]. Besides, the efficiency is still as high as 31% at 3000 suns. We have extended this strategy to lattice-matched GaInP/Ga(In)As/Ge triple junction solar cells (TJSC). At the current state of development, our cells show an efficiency of 36.2% at 700 suns [11].

Furthermore, the active area of our cells is about 1 mm², which is close to the optimum value, in accordance to the compromise situation imposed by the series resistance, perimeter recombination, packaging cost and heat dissipation for an operation of the device at 1000 suns. The resulting geometrical dimensions of the device make it appropriate to use the "LED-like approach" [6] for the post-growth processing of the semiconductor structure.

For the sake of obtaining high efficiencies at ultra-high concentrations, we analyze in this paper the factors limiting the efficiency of our current triple junction solar cells. If these limiting factors (namely a low band gap top cell, an absorbing tunnel junction and a significant current mismatch) are overcome, the theoretical modeling carried out, based on realistic technological improvements, shows that an efficiency over 41% at 1000 suns is reachable. The first improvements have been already experimentally achieved and are presented here.

RESULTS

Figure 1 summarizes the external quantum efficiency (EQE) of the lattice matched (LM) GaInP/Ga(In)As/Ge triple junction solar cells manufactured in-house (EQE of Ge subcell not plotted for the sake of clarity).

The overall result is that the device is middle cell limited with a short circuit current of $J_{SC} = 13.3 \text{ mA/cm}^2$ (AM1.5D ASTM G173 normalized to 1000 W/m²), being the current in the top cell $J_{SC,TC} = 14.2 \text{ mA/cm}^2$. This situation reveals a relatively large current mismatch of around 6.5% that

can be easily corrected adjusting the thickness of the top and middle subcells.

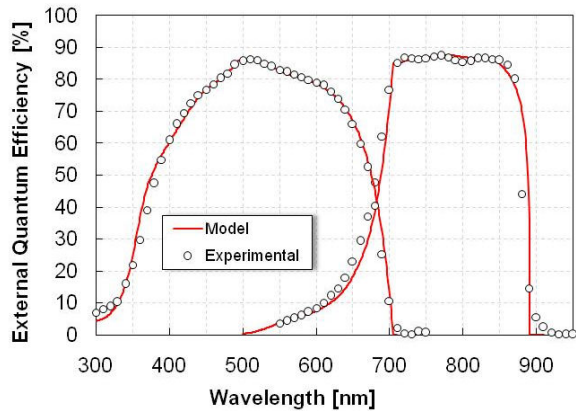


Figure 1. External quantum efficiency (EQE) of the triple-junction solar cells (TJSC) developed. The red line represents the modeling of such EQE. The EQE of the Ge subcell in the TJSC is not shown for clarity.

Figure 2 presents the concentrator results of the triple-junction solar cells developed, showing that the efficiency is over 36% for concentrations between 550 and 850 suns, peaking at 700X with a 36.2% [11].

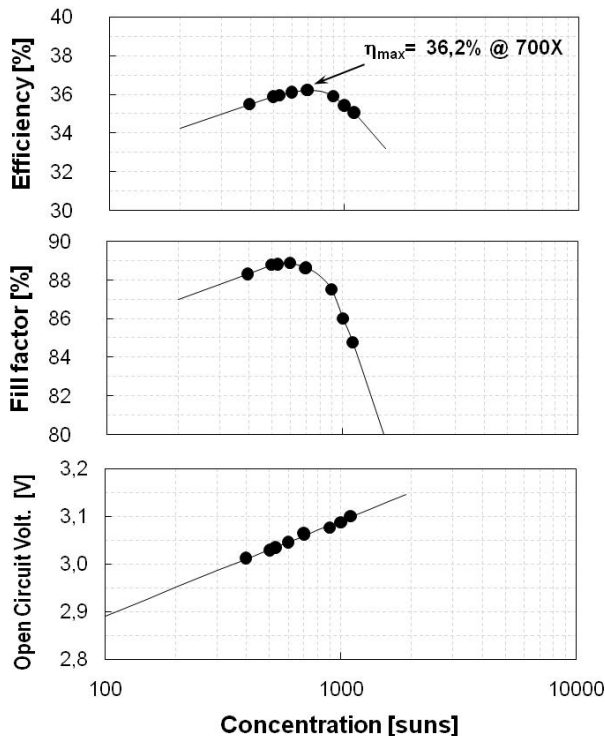


Figure 2. Concentration response of the triple junction solar cell whose EQE is shown in figure 1.

DEVICE IMPROVEMENT ANALYSIS

A detailed analysis of the solar cells developed has been carried out in order to establish a clear diagnosis of their limitations and, consequently, a roadmap to attain efficiencies over 40% at 1000 suns. Figure 3 visually illustrates such roadmap, by means of iso-efficiency contours of 1000-sun J_{SC} and V_{OC} that yield efficiencies from 36% to 40% at 1000 suns. This figure assumes that the FF evolution in Fig 2 can be maintained (namely $FF=86.0\%$ at 1000 suns) as improvements in J_{SC} and V_{OC} are materialized (i.e. junction quality and series resistance remain unaffected). Additionally, it is also assumed the linearity of J_{SC} vs concentration (hence the following discussions will be based on the one-sun J_{SC} or $J_{SC,1X}$). In this figure, the current design is marked as a filled black circle. Other markers represent some improved designs that steadily approach the $\eta = 40\%$ target.

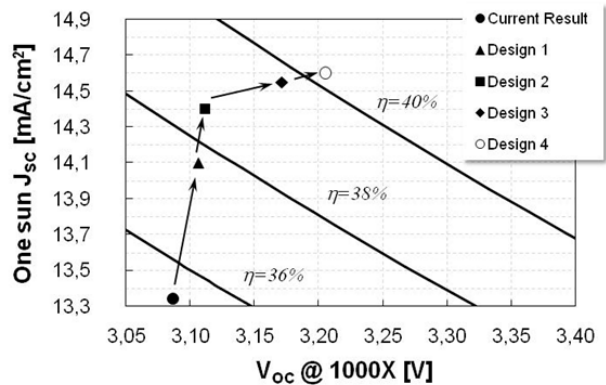


Figure 3. Iso-efficiency contours of J_{SC} and V_{OC} at 1000 suns to attain 36% to 40% efficiency at 1000 suns (FF is assumed to be the experimental value in fig.2, $FF= 86.0\%$). The corresponding J_{sc}/V_{oc} pairs for current result (Fig 2) and several improvements on this design are also indicated.

The modeling of the EQE of the device (fig. 1) revealed a defective design in the middle cell. On the one hand, its thickness (2500 nm) was clearly insufficient and some interferometric reflections in upper layers were causing unexpected reflection losses. These facts were corrected in *Design #1* and subsequently current matching at $J_{SC,1X} = 14.1 \text{ mA/cm}^2$ can be attained (corresponding EQE depicted in Figure 4) together with a slight increase in V_{OC} (~20 mV).

Design #2 implements a high band gap cathode ($n^{++}\text{GaInP}$) in the top tunnel junction and a slight correction in the thickness of the top cell. With these changes the I_{sc} can be further increased to $J_{SC,1X} = 14.4 \text{ mA/cm}^2$, which in turn causes a slight increase in V_{OC} .

Design #3 represents the use of surfactant-mediated growth to raise the band gap of the top cell to ~1.81 eV and subsequent rearrangement of thicknesses for current

matching. This approach would increase the V_{OC} in some 60 mV and J_{SC} would be raised to $J_{SC,1X} = 14.55 \text{ mA/cm}^2$.

Finally, *Design #4* includes a final tuning of the window/emitter interface of the top cell, and a new increase in the top cell band gap to 1.83 eV. These changes would elevate the short circuit current to $J_{SC,1X} = 14.60 \text{ mA/cm}^2$, while a further boost in V_{OC} can be achieved to reach $V_{OC} = 3.206 \text{ V}$ and thus get a final efficiency of 40.3% at 1000X. In this final stage our design would show slightly lower figures than those reported for the record lattice matched triple junction cell [3] at 1000X ($J_{SC,1X}=14.67 \text{ mA/cm}^2$, $V_{OC} = 3.270 \text{ V}$, $E_{gTC}=1.84 \text{ eV}$), though with a significantly higher fill factor (86% vs. 83%). The evolution of the EQE throughout all these designs can be followed in figure 4.

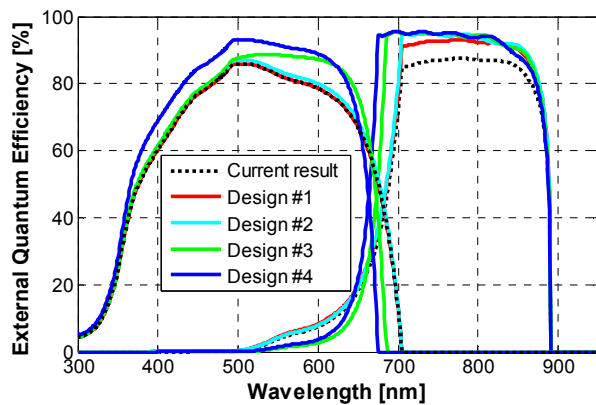


Figure 4. Evolution of the EQE of the top and middle cell from Design #1 to Design#4.

Last, there is further room for improvement regarding the FF . In the world record dual-junction solar cell, the FF achieved at 1000X was 88% [12], 2% higher than the experimental value of our solar cells, considered for this device analysis. We believe that this difference is due to a defective processing of the front contact. When such high FF are reproduced in the triple junction, its efficiency will be 41.2% at 1000X.

EXPERIMENTAL PROGRESS

The experimental implementation of the aforementioned roadmap is not straight forward. However significant progress has been made so far. For instance, improvements in the middle cell have been implemented resulting in a significant increase in its J_{SC} ($\sim 1 \text{ mA/cm}^2$). On the other hand, Figure 5 shows the J-V curve of the high band gap tunnel junction implemented (with an AlGaAs-based anode and a GaInP-based cathode), as grown and after a 30-min long anneal at 675°C in order to simulate the thermal load suffered by the tunnel structure inside the MOVPE reactor when a complete triple junction structure is grown. The “as grown” device presents a very high peak current (3 kA/cm^2) and a low series resistance

($2.8 \cdot 10^{-4} \Omega \cdot \text{cm}^2$) while J_{SC} is reduced to about 730 A/cm^2 and the series resistance is raised to $1.5 \cdot 10^{-3} \Omega \cdot \text{cm}^2$ after the annealing process. However, the values of these figures of merit are still good enough to use these tunnel junctions in the final triple junction solar cell structure. For instance, in the inset of Figure 5, it can be seen that the voltage drop at a current injection of 14 A/cm^2 (the expected J_{SC} of a TJSC working at 1000X) is merely 20 mV.

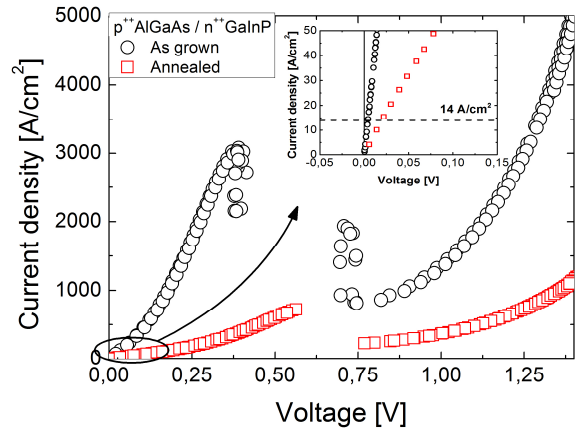


Figure 5. J-V curve of the high band gap tunnel junction implemented, for the cases “as-grown” and annealed 30 min at 675 °C.

SUMMARY AND CONCLUSIONS

High efficiency solar cells working under ultra-high concentrations ($>1000X$) seem to be a promising solution to decrease the cost of PV electricity, increase the efficiency and circumvent the material availability restrictions for massive PV penetration. A detailed analysis of the limitations of our current triple junction solar cell (36.2% at 700X) in the quest to maximize its efficiency at 1000X, has led to the description of a roadmap to reach an efficiency over 41%. In order to follow this roadmap, a proper high band gap tunnel junction for ultra-high concentrations has already been successfully developed. The other required improvements are currently under development.

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