STRUCTURAL CHALLENGES IN MULTIJUNCTION SOLAR CELLS FOR ULTRA-HIGH CPV

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ABSTRACT: The paths towards high efficiency multijunction solar cells operating inside real concentrators at ultra high concentration (>1000 suns) are described. The key addressed factors comprehend: 1) the development of an optimized tunnel junction with a high peak current density (240 A/cm^2) to mitigate the non-uniform light profiles created by concentrators, 2) the inclusion of highly conductive semiconductor lateral layers to minimize the effects of the non-uniform light profiles in general, and the chromatic aberration in particular; and 3) an adequate design of reliability studies to test multijunction solar cells for real operation conditions in order to determine the fragile parts in the device and improve them. These challenges are faced by means of experimental and theoretical investigation using a quasi-3D distributed circuital model.

Keywords: multijunction solar cell, CPV, solar concentrator, tunnel junction, reliability

1. INTRODUCTION

Concentrator photovoltaic systems (CPV) seem to be one of the most promising ways for solar energy to generate electricity at competitive prices for the next decades [1]-[5]. The general trend shown in [4] evidences that the hierarchy of factors impacting the cost of the electricity produced by CPV systems are: first learning (i.e. decrease in cost brought about just by cumulated production), second concentration level and third efficiency of the solar cell. Regarding the learning, CPV is just at the beginning of its learning curve as an industry with a considerable potential for technical and manufacturing improvements. In this respect, CPV industry needs to achieve volume productions in the range of tens of megawatts per year to achieve low costs [3]. Regarding efficiency, a CPV system consists of solar cells and optical elements, integrated into modules, eventually mounted on a tracking system. To become cost-competitive significant improvements in all of the parts of the system as well as in the system integration itself are required. Multijunction solar cells have achieved increasingly impressive efficiencies in recent years. The current record efficiency is 43.5 % by Solar Junction [6] but there are seven multijunction solar cell architectures with reported efficiencies in the 40% range [3]. The module and system efficiencies have also increased significantly. Amonix and SEMPRIUS have both reported module efficiencies over 33% [7]. Finally, the determination of the most recommendable concentration range still remains as an open issue. On one hand, most CPV manufacturers have designs with nominal concentrations in the range of 400-700 suns. On the other hand, the use of ultra-high concentrations (X > 1000 suns) still quite unexplored, pays back in the form of a dramatic reduction in the levelized cost of electricity produced [5] but tremendous challenges in multiple ways have to be engineered satisfactorily.

State-of-the-art commercial multijunction solar cells typically have their peak efficiency around 500 X or less. At higher concentrations their efficiency drops either because the increase of open circuit voltage with concentration cannot counterbalance the decrease in fill factor resulting from resistive losses or because the peak current of the tunnel junction (TJ) is surpassed. Classically, when facing the design challenges in PV devices associated to concentrator operation the focus has been put on the layout of the front metal grid. Despite this being an indispensible factor for a good operation at high irradiances, there are other more subtle challenges to deal with. Accordingly, in this paper we focus on describing the optimization carried out in our lattice matched GaInP/Ga(In)As/Ge multijunction solar cells to overcome some of the challenges that the ultra-high concentration regime imposes on the photovoltaic converter. The key developments in this quest include:

   a) Optimization of tunnel junctions in order to achieve high efficiencies at ultra-high concentrations.
   b) Addition of semiconductor layers to minimize the impact of non-uniform light profiles in both irradiance and spectral distribution.
   c) Reliability studies in MJSCs in order to evaluate and quantify failures and to understand the failure mechanism in order to avoid them.

The optimization of the multijunction solar cell has been guided by extensive experimentation as well as the exhaustive use of our quasi-3D distributed circuital model.

## 2. TUNNEL JUNCTIONS FOR UHCPV

The concentrator optics in any CPV set-up will increase the irradiance on the solar cell at the price of producing variations in the spatial distribution of the light. In the case of ultra-high CPV (UHCPV) –where concentrator optics produce nominal irradiances of 1,000 suns or higher– this situation is even more drastic and peak irradiances a factor of 5 times the nominal (i.e. average) irradiance are common. This fact implies that some regions in the active area of the solar cell are working at irradiance levels well above the nominal concentration and thus the solar cell design has to consider this overstress.

In this respect, the tunnel junction is one of the most critical parts in a multijunction solar cell. TJs have to act as efficient interconnections between subcells adding negligible losses (optical and electrical). This implies that, on one hand, the TJ should present a high optical transmittance, which can be accomplished by simply selecting materials with a band gap higher than the band gap of the underlying subcells. On the other hand, in terms of electrical performance, for UHCPV operation

the TJ should present a high conductance in the ohmic region, as well as 1) high peak current (J_p) and 2) a low voltage drop.

In this paper we present the electrical characterization (Figure 1) of a tunnel junction based on p^{++}AlGaAs/n^{++}GaInP designed for UHCPV. This design presents an outstanding peak current density J_p=950 A/cm² for as-grown samples, whilst it decreases to a still outstanding J_p=240 A/cm² for samples annealed at 675ºC for 30 minutes. Such peak current makes it suitable for operation at concentration levels up to 17,800 suns (assuming the short circuit current density at 1 sun, $J_{sc@1X} = 13.5$ mA/cm²). The suitability of the TJ designed for real operation conditions can be assessed with the simulations shown in figure 2, where the difference in performance between the TJ implemented and other design with a peak current density of 40.5 A/cm² (which might be considered to be sufficiently high for a device designed to operate at 1,000 X), is addressed. Figure 2 shows the simulation of the I-V curves of multijunction devices with the tunnel junctions afore described, working under Gaussian illumination with a nominal concentration of 1,000 X and a peak-to-average ratio (PAR) of 3.5. In the case of the TJ with the lowest J_p, the dip is clearly observable in the I-V curve. However, what is more important in this particular case is that the maximum power point (MPP), I_{SC} and V_{OC} of both devices are very similar. So if we only pay attention to the key points in the I-V curve we may overlook the presence of the dip, which would have a deleterious effect in real operation (where excursions from the MPP are not uncommon).

Therefore, the tunnel junction presented in this paper can be integrated in a multijunction solar cell designed to work at virtually any practically achievable concentration. Even though high non-uniform irradiance profiles are produced by the concentrator optics used, with this TJ a good FF is assured.
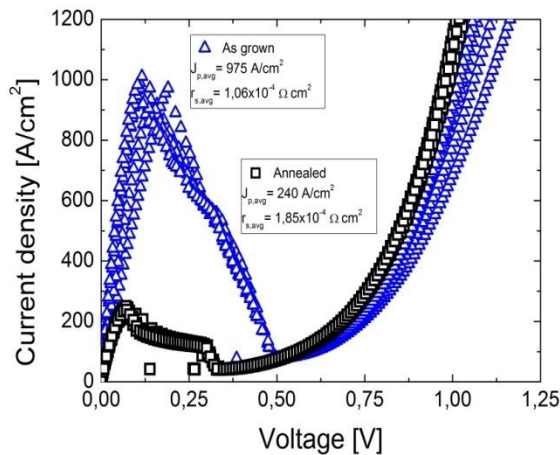
Figure 1. Experimental J-V curves of p^{++} AlGaAs/ n^{++}GaInP tunnel junctions. The curves in blue triangles represent the 'as grown' structure; whilst the black squares represent the same structure annealed at 675ºC for 30 minutes. The multiple curves included reflect a small dispersion in the results. Average values for the peak current and the equivalent resistance are included in the labels.
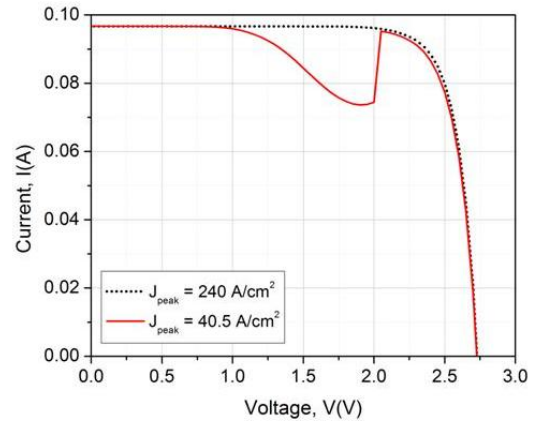
Figure 2. Simulation using the quasi 3D distributed model presented in [8] of two dual-junction solar cells with different tunnel junctions working under a Gaussian illumination profile with a nominal concentration of 1,000 X and a peak-to-average ratio of 3.5. A J_{sc} = 13.5 mA/cm² at 1 X is assumed.

3. MITIGATING THE EFFECTS OF CHROMATIC ABERRATION

In addition to the variable distribution of irradiance, already mentioned; concentrator optics also produces, to some extent, chromatic aberration. This is to say, superimposed to the irregular distribution of irradiance, there is a change with location in the spectrum impinging each point of the solar cell active area. In real operating conditions, the spectrum may change considerably throughout the day, from season to season and from location to location. In this respect, it would be desirable to include in the solar cell design some feature that could minimize the impact of chromatic aberration.

We have studied this effect with our advanced 3D distributed model presented in [8]-[9], and concluded that the inclusion of highly conductive lateral conduction layers is a key factor to minimize the impact of chromatic aberration. These layers (which may be implemented by tuning the growth conditions of the BSFs or barrier layers around the tunnel junction) provide the paths for current redistribution and thus minimize the effects of having a fraction of the multijunction solar cell being top-cell limited while the rest of its area is middle-cell limited.

In order to analyze the impact of chromatic aberration, Gaussian light profiles with a Peak to Average Ratio of 4 (PAR = 4) and PAR = 2 (peak 2000 X and average 1000 X) as shown in figure 3 have been used. Two simulation cases have been considered: (a) top-cell illuminated with profile PAR_{TC} = 4 and middle-cell illuminated with profile PAR_{MC} = 2; and (b) the opposite case (PAR_{TC} = 2 and PAR_{MC} = 4). Details of the simulation procedure and the device being simulated can be found elsewhere [10]. Figure 4 shows the I-V curve calculated for a dual-junction solar cell illuminated in cases (a) –dashed line– and (b) –dotted line– being the nominal concentration of 1,000 X in both situations. As shown by figure 4, when the top cell is illuminated with the profile having the highest PAR, the effects on the I-V curve are drastic and a dip in the I-V curves appears as a result of the device having a current density above the peak current of the tunnel junction at some locations (particularly at the areas receiving the peak of the

Gaussian illumination profile). Excursions from the MPP may cause the solar cell to operate within the dip region where its output power is severely degraded. On the contrary, this situation changes in the case when the middle cell is excited with the highest PAR profile, since the back contact efficiently redistributes the excess current density. Accordingly, the fill factor in this situation is much higher and the dip is not observable.

In order to assess the key influence of lateral current redistribution paths, figure 4 also includes simulations of cases (a), (b) for devices in which the tunnel junction has been redesigned to minimize its lateral resistance. These simulations (in blue and red lines) are quite similar to the corresponding curves in the former case in the vicinity of the MPP. However, in this new design the dip has disappeared in the case when the top cell is illuminated with the profile having the highest PAR. Accordingly, in this new design a small excursion from the MPP will not cause a major impact in its output power. This fact will have no impact if characterizing the devices at standard test conditions, but will cause a great difference in terms of annual energy yield between both designs.
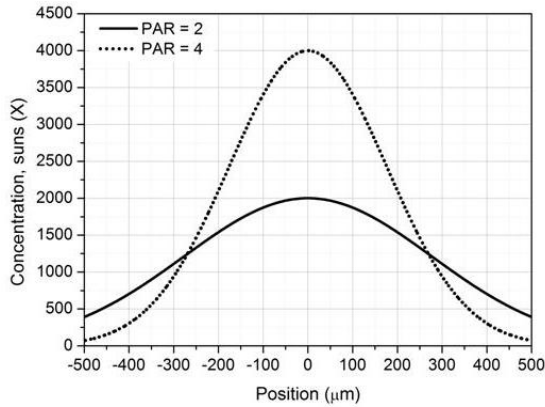
Figure 3. Gaussian irradiance profiles used to calibrate the impact of chromatic aberration. Nominal concentration of both profiles is 1000 suns, though peak-to-average ration is 2 for the solid line and 4 for the dotted line**.**
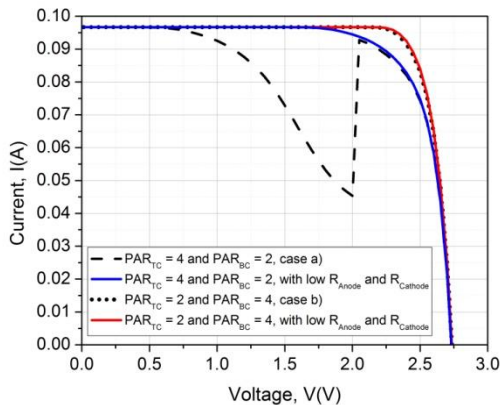
Figure 4. Simulation using the quasi 3D distributed model presented in [8] of the I-V curve of a dual-junction solar cell at the four situations described in the text.

4. RELIABILITY STUDIES

The CPV community is aware of the fact that together with the efficiency increase, high reliability is essential in reducing the cost of solar electricity by extending system lifetime [11]. Multijunction solar cells must be very reliable devices if warranties similar to those of conventional silicon solar cells are to be offered (25 years). Taking into account that the degradation of optical elements and failures in the performance of the trackers may occur [12], the margin for degradation or failure of the solar cells during their expected lifetime should be very low. Up to now, there is not enough accumulated experience to evaluate the reliability of high concentrator multijunction solar cells because they have not been in the field long enough. Therefore, accelerated life tests to find out how, when, and why failures occur in the solar cells in a moderate period of time (weeks/ months) are required. We have carried out a temperature accelerated life test (ALT) in GaAs single-junction solar cells of 1 mm^2 [13] designed to work at 1,000 X, and by the analysis of the gradual failures we have determined that the failures were caused by perimeter degradation [14]. Therefore, thanks to the accelerated life test we know that in order to increase the reliability of these devices we need to work on electrically insulating these solar cells or passivating the perimeter. Currently, similar studies are being carried out on triple-junction solar cells in order to determine their reliability and the fragile parts in their structure.

5. SUMMARY AND CONCLSUIONS

Ultra-high CPV is a strategy with great potential for the massive deployment of solar electricity. However, in order to operate at a concentration higher than 1,000 X several structural challenges in the design of multijunction solar cells have to be faced. In this paper we have focused on overcoming three problems: the design of the TJ, chromatic aberration and the reliability of the solar cells. Regarding the TJ, we have presented the characterization of a tunnel junction based on AlGaAs/GaInP with a peak current density equivalent to 17,800 X. Therefore, this TJ can be used to work at virtually any practically achievable concentration or under extremely non-uniform irradiance profiles. Regarding chromatic aberration, we have studied how to minimize its negative effect on the multijunction solar cell's behavior by using low resistive layers in the TJ. These layers are able to better redistribute the excess of photo-generated current in some regions of the solar cell. Finally, concerning reliability, we are currently carrying out accelerated life tests on triple-junction solar cells in order to identify fragile parts in these solar cells and accordingly introduce the structural changes required.

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