OPTICAL TRANSMITTANCE MAXIMIZATION IN SUPERIOR PERFORMANCE TUNNEL JUNCTIONS FOR VERY HIGH CONCENTRATION APPLICATIONS

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ABSTRACT: The light transmission through a tunnel junction in a multijunction solar cell depends on the optical properties and thickness of the whole solar cell layers stack, which configure the light absorption, reflection and interference processes taking place inside the semiconductor structure. In this paper the focus is put on the AlGaAs barrier layers of p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions inserted into a GaInP/GaAs dual-junction solar cell. The aim is to analyze the effect of the thickness and Al-composition of these barrier layers on the light transmittance of the tunnel junction, using the bottom cell J_{sc} as the merit figure to appraise it. An intricate relation between this J_{sc} and the barrier layers parameters, caused by interferential reflectance, was observed. The importance of an appropriate optical design of the semiconductor structure was corroborated by a non-negligible gain in the bottom cell J_{sc} when choosing the appropriate barrier layers Al-compositions and thicknesses from a range of practical values for which the optical absorption is not the main contributor to the optical losses.

Keywords: multijunction solar cell, tunnel junction, optical losses

1 INTRODUCTION

Monolithic multijunction solar cells have achieved the maximum conversion efficiencies under concentrated light [1]. In these kind of solar cells, the tunnel junctions used to series connect the subcells in the multijunction stack play a crucial role. Both their electrical and optical properties determine the performance of the multijunction solar cell. On the one hand, a high peak tunneling current together with a low voltage drop across the tunnel junction and a low optical absorption are required. On the other hand, the optical transmission through the tunnel junction semiconductor structure must be maximized in order to obtain the highest J_{sc} in the subcells underneath and, consequently, in the whole multijunction solar cell.

The best tunnel junction electrical characteristics are attained when low band gap materials are used, since they favor the band-to-band tunneling through a lower potential barrier height, as compared to high band gap materials. The GaInP/GaAs dual-junction solar cells developed at the Solar Energy Institute – U.P.M., exhibit a record efficiency at 1000 suns of 32.6 % and an excellent performance at higher concentrations (higher than 31% at 3000 suns) [2]. The tunnel junction used in these dual-junction solar cells is based on a p^{++}AlGaAs/n^{++}GaAs heterostructure doped with carbon and tellurium. The use of the appropriate growth conditions led to the attainment of an electrical performance in these tunnel junctions unparalleled by any other tunnel junction grown on GaAs or Ge substrates. In fact, as shown in Figure 1, a peak current density as high as 10100 A/cm^2 and a series resistance at 0 V bias as low as $1.6 \cdot 10^{-5}$ Ω·cm^2 was obtained. These electrical characteristics are far better than necessary for the attainment of an excellent performance in the dual-junction solar cell, concerning series resistance, for any light concentration achievable on Earth.

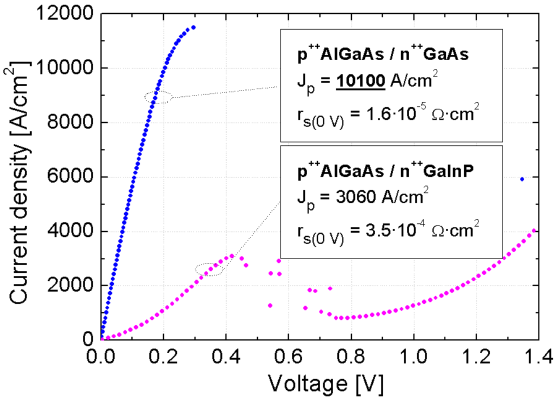

Figure 1: J-V curve of high performance p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions developed at I.E.S.-U.P.M.

However, the lower optical transmission exhibited by low band gap tunnel junctions, as compared to higher band gap approaches, gives rise to a lower J_{sc} in the multijunction solar cell. The use of high band gap tunnel junctions, typically based on p^{++}AlGaAs/n^{++}GaInP heterostructures in the context of the multijunction solar cells [3], allows the achievement of higher J_{sc} in the solar cell, but, in general, leads to worse electrical properties and a higher complexity in their development, concerning the MOVPE growth of their semiconductor structure. The results obtained so far in our laboratory concerning high band gap tunnel junctions based on the p^{++}AlGaAs/n^{++}GaInP heterojunction exhibit a series resistance more than one order of magnitude higher than in the case of the p^{++}AlGaAs/n^{++}GaAs tunnel junction, as can be observed in Figure 1. This series resistance is comparable to the contributions of other parts of the concentrator solar cell, such as the metal contacts or the substrate. However, the electrical characteristics (peak current density and series resistance) exhibited by this high band gap tunnel junction are still suitable to obtain an appropriate performance of the multijunction solar cell at high concentrations.

Therefore, once our development work has led to the attainment of the appropriate electrical properties in these tunnel junctions, the analysis and optimization of their optical properties were addressed. The aim of this paper is to examine theoretically the possibility of increasing the light transmission in both kinds of tunnel junctions, i.e., the low and high band gap cases, by evaluating the effect of modifications in the semiconductor layers composing the tunnel junction on the J_{sc} of the solar cell, without affecting the electrical performance of the tunnel junction.

2 APPROACH

Simplistically thinking, the optical transmission in a tunnel junction can be maximized if the optical absorption in each of its layers is minimized. However, in practice, not only optical absorption occurs as the light traverses the semiconductor layers of the multijunction solar cell, but also reflection and interference processes take place. The actual optical transmission through the tunnel junction is, thus, determined by the aggregate of all these processes. Moreover, the light transmission through the tunnel junction structure depends not only on the properties of its semiconductor layers but also on the properties of the rest of layers composing the multijunction solar cell stack, which do have a role in the interferential processes commented above.

Therefore, the theoretical approach to be used in this study must be able to take into account all the optical processes taking place in the multijunction stack. This was accomplished by applying the Transfer Matrix method [4,5] to calculate the optical reflection, absorption and transmission of the semiconductor stack under study. The data output was then used to compute the carrier generation in the photoactive layers of the bottom cell and then its J_{sc} for the AM1.5d ASTM-g173 solar spectrum, assuming a minority carrier collection efficiency equal to unity. The optical data used for GaAs, GaInP and AlGaAs with different compositions was taken from the literature [6,7].

The electrical properties of the tunnel junction are determined primarily by the characteristics (material, thickness and doping level) of the anode and cathode. We have observed that the AlGaAs barrier layers used in our case are important when integrating the tunnel junction into the dual-junction solar cell structure, for example by avoiding the formation of parasitic junctions. However, they contribute little to the attainment of the superior electrical characteristics observed in our tunnel junctions [8]. Therefore, we are going to focus on the effect of the barrier layers on the optical transmission through the tunnel junction, keeping the anode and cathode characteristics constant in order not to interfere with the electrical properties of the tunnel junction. In Figure 2, the whole dual-junction solar cell semiconductor structure used in this study is shown.

3 RESULTS AND DISCUSSION

As pointed out before, we have restricted our analysis to modifications in the composition and thickness of the AlGaAs barrier layers (see Figure 2). On the one hand, the material composition affects the refractive index contrast between the different layers of a heterojunction and, consequently, it modulates the intensity of the internal reflections taking place. Obviously, the composition affects also the absorption in these layers. On the other hand, both the composition and thickness determine the characteristics of the interferences occurring in the heterojunction and, as a result, they have a direct influence on the magnitude and shape of the spectral reflectance due to these interferences.

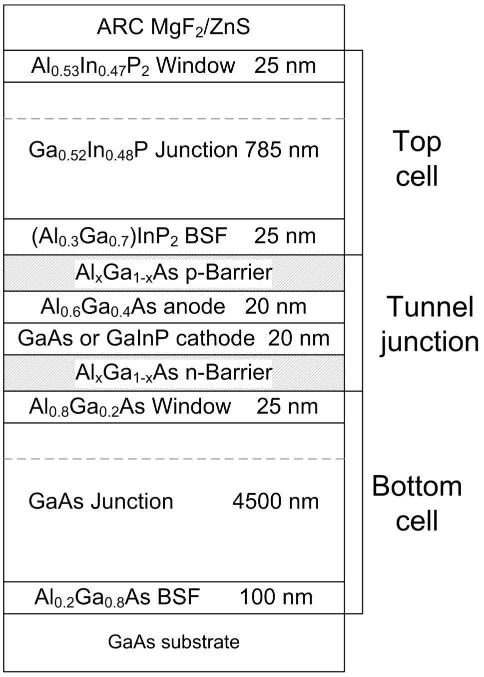

Figure 2. Dual-junction solar cell semiconductor structure used in the theoretical analysis of the optical transmission through the tunnel junction. Only the characteristics of the semiconductor layers relevant for the optical study are indicated.

Therefore, we have four freedom degrees in our study: composition and thickness of the p-barrier and n-barrier. We have used an iterative process in order to find the optimum values of these parameters in terms of light transmission to the bottom cell by computing its J_{sc}. In first place, the composition of each barrier layer was swept, for the two tunnel junctions under study. The thickness of each barrier layer was set to 50 nm as an initial “reasonable” guess-value. The results are shown in Figure 3.

As can be observed, the highest light transmission to the bottom cell is produced for an Al composition of the 50 nm barriers around 50% for the p^{++}AlGaAs/n^{++}GaAs tunnel junction, and around 60% for the p^{++}AlGaAs/n^{++}GaInP. This demonstrates that absorption is not the only optical process determining the transmittance of the tunnel junction, as commented before. Otherwise the maximum light transmission would occur for the highest composition in these layers. In fact, the absorption is most important for Al compositions below the direct-to-indirect transition of AlGaAs (around 45% of Al). In this range of compositions the bottom cell J_{sc} decreases fast as the Al composition is reduced, as can be observed in Figure 3. For compositions above this value the interference-related reflectance becomes the primary cause of the reduction of the bottom cell J_{sc}. The optimum barrier layer Al composition is determined by the tradeoff between absorption and interference processes.

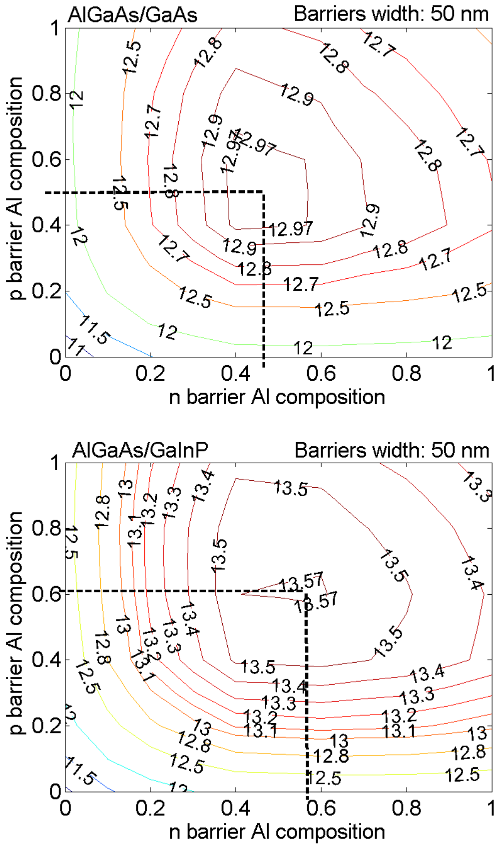

Figure 3. J_{sc} [mA/cm^2] contour plots of the bottom cell of Figure 2, against the barrier layers Al composition, for the cases of an p^{++}AlGaAs/n^{++}GaAs (top) and p^{++}AlGaAs/n^{++}GaInP (bottom) tunnel junction.

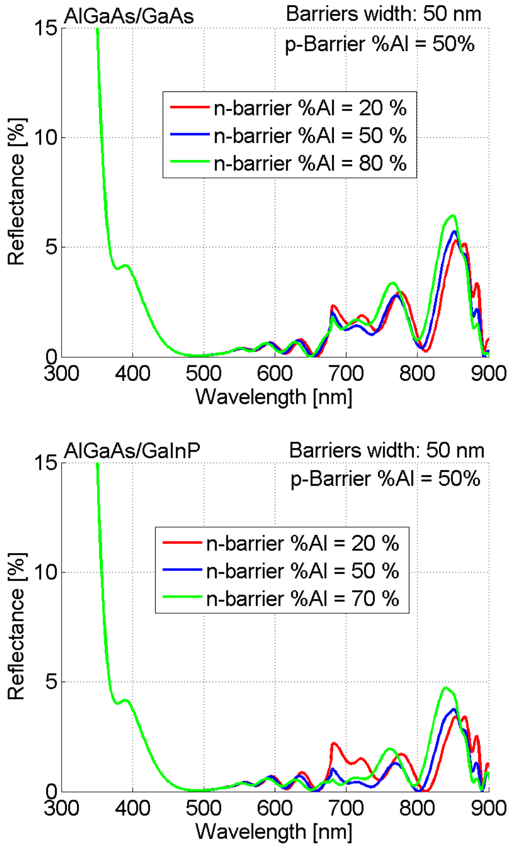

Figure 4. Calculated spectral reflectance of the structure shown in Figure 2 with p^{++}AlGaAs/n^{++}GaAs (top) and p^{++}AlGaAs/n^{++}GaInP (bottom) tunnel junctions, for different compositions of their n barriers.

The effect of the properties of the barrier layers on the reflectance is illustrated in Figure 4, where the calculated spectral reflectance of the dual-junction solar cell semiconductor structure being studied is shown for the cases of using p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions, for different Al compositions of the AlGaAs n-barrier. It can be clearly observed how the reflectance increases as the n-barrier Al composition is made higher than the optimum, according to Figure 3. For Al compositions lower than the optimum, the integrated reflectance does not increase so clearly, but the J_{sc} of the bottom cell decreases more importantly than for higher Al compositions, as shown in Figure 3. This indicates that the light absorption is governing the influence of the barrier layer properties on the bottom cell J_{sc}, as expected.

On the other hand, quantitatively speaking, it can be observed how the variations in the reflectance are quite small (observe the scales in Figure 4). This translates into the fact that the variations in the bottom cell J_{sc}, for barrier layers Al composition above the optimum, i.e., in the range where the interference processes are governing the tendencies, are smooth, as can be observed in Figure 3. This makes that there exist a range of compositions around the optimum value which produce virtually the same bottom cell J_{sc}.

The influence of the thickness of the barrier layers on the optical transmittance of the tunnel junction was studied in the next step of the iterative process we followed. This step consisted on sweeping the thickness and composition of each barrier layer, by keeping the characteristics of the other one in the optimum value obtained in the previous step of the iteration. After several iterations, the method converged, giving a solution for the optimum thickness and composition of both barrier layers. The results are shown in Figure 5.

Several comments can be done about the results obtained. First, the optimization of both the composition and thickness of the barrier layers, as compared to the initial optimization that took only their composition into account, gives rise to a higher maximum bottom cell J_{sc} by around 0.15 and 0.1 mA/cm^2 for the p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions, respectively. Second, the optimum thickness was found to be around 100 nm for the n and p barriers, in both the p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions. The optimum Al composition obtained was around 80% and 90%, respectively. Note how, oppositely to what one could intuitively expect, a considerably thick barrier layer with an Al composition lower than the maximum is producing the highest optical transmission through the tunnel junction. On the other hand, and similarly as observed in the barrier layers composition study shown in Figure 3, the variation of the bottom cell J_{sc} for values of the thickness and composition of the barrier layers around their optimum is quite smooth. This means that there exist a range of compositions and thicknesses that give rise to virtually identical bottom cell J_{sc}.

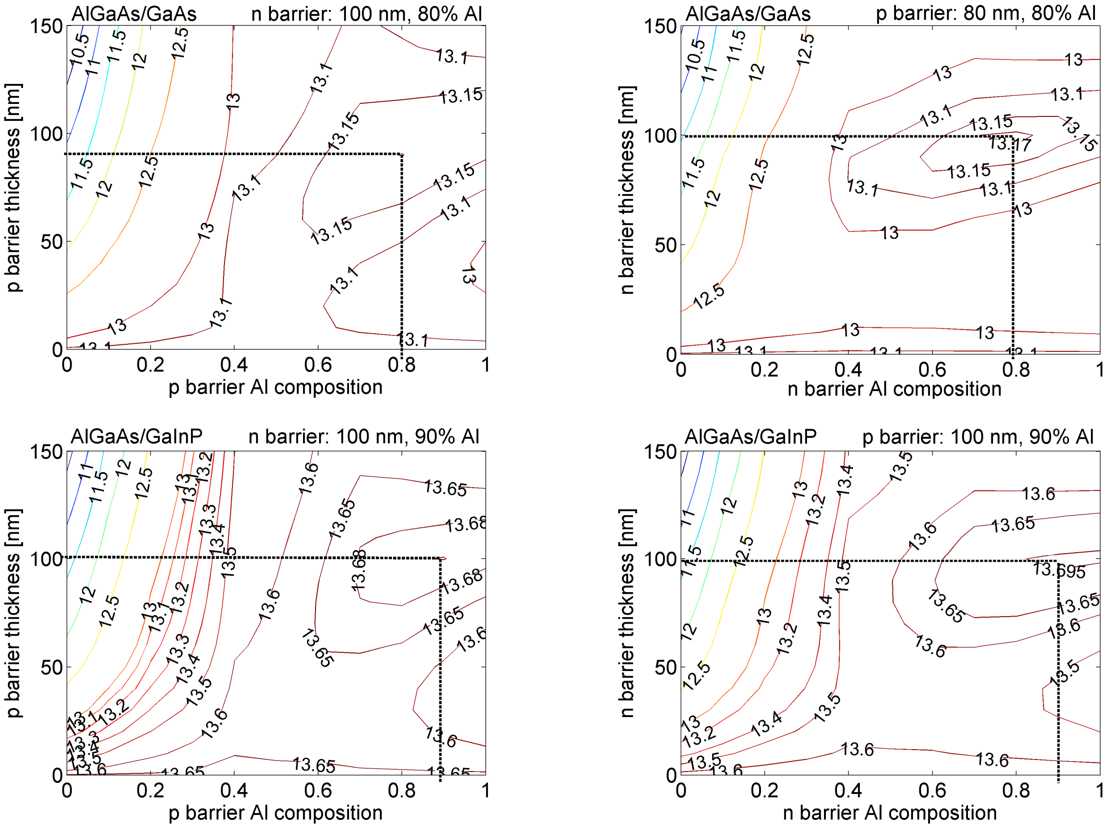

Figure 5. Bottom cell J_{sc} [mA/cm^2] contour plots, against the n (right) and p (left) barrier layer thickness and Al composition, for the p^{++}AlGaAs/n^{++}GaAs (top) and p^{++}AlGaAs/ n^{++}GaInP (bottom) tunnel junctions.

Nevertheless, it must be taken into account that the results shown in the contour plots of Figure 5 for each barrier layer are linked to a value of composition and thickness of the other barrier layer. As soon as one parameter of one barrier is modified, the evolution of the J_{sc} with variations in the parameters of the other barrier layer is different, giving rise to an intricate cross-relation between the barrier layers parameters and the bottom cell J_{sc}. This means that the minimum J_{sc} that can be obtained cannot be determined, in principle, from the data presented in Figure 5, since it can occur for a combination of the four parameters being studied which is not contemplated in the contour plots shown.

In order to estimate the J_{sc} gain obtained when using the optimized barrier layers, with respect to a "generic" case, the J_{sc} was calculated for a range of barrier layers thicknesses and Al compositions. This range was restricted to reasonable values concerning practical issues. Concretely, the minimum thickness used was 20 nm. Thinner barrier layers are not expected to be functional for their purpose of eliminating the interaction of the tunnel junction growth with the top cell growth, or to eliminate possible parasitic junctions, which are the two main purposes of their use in the multijunction solar cells developed in our laboratory. The upper thickness limit was chosen to be 150 nm, in order to extend the thicknesses range above the optimum value which was found to be around 100 nm, as shown in Figure 5. Besides, the range of compositions explored was from 40% to 80%. The lower limit was decided to be 40% since lower compositions are well known to produce an important light absorption in the wavelength range of photons which can be absorbed in the bottom cell. The upper limit of 80% is chosen as the maximum composition usable without restrictive problems concerning the doping (specially n-type doping), lattice matching and morphology of the AlGaAs layers, according to our experimental evidence. The results of the bottom cell J_{sc} calculation for this range of barrier layer parameters are summarized in Table 1.

Table 1. Calculated n and p barriers Al composition and thickness needed to obtain the maximum and minimum bottom cell J_{sc}, which are also indicated, for p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions.

Tunnel junction		**n barrier %Al Thickness**	**p barrier %Al Thickness**	**Bottom cell J_{sc}**
AlGaAs GaAs TJ	J_{sc} max	80% 100 nm	80% 90 nm	13.18 mA/cm^2
	J_{sc} min	80% 40 nm	80% 40 nm	12.72 mA/cm^2
	J_{sc} difference			**0.46** mA/cm^2
AlGaAs GaInP TJ	J_{sc} max	80% 90 nm	80% 90 nm	13.69 mA/cm^2
	J_{sc} min	40% 80 nm	40% 150 nm	13.36 mA/cm^2
	J_{sc} difference			**0.33** mA/cm^2

The maximum bottom cell J_{sc} value, and the thicknesses and Al compositions of the barriers that produce it, were already known from the calculations summarized in Figure 5. Concerning the minimum bottom cell J_{sc} value, for the p^{++}AlGaAs/n^{++}GaAs tunnel junction it is obtained for a composition of 80% and a thickness of 40 nm in both barriers. This high Al composition and low barrier thickness evidences, again, the fact that the optical absorption is not the predominant optical process. As can be observed in Figure 6, these barrier layers properties give rise to an important reflectance for photon wavelengths above the band gap of GaInP (around 670 nm). As for the p^{++}AlGaAs/n^{++}GaInP tunnel junction, the minimum bottom cell J_{sc} is obtained for a barrier composition of 40%, a n-barrier thickness of 80 nm and a p-barrier thickness of 150 nm. Though lower than in the case of the p^{++}AlGaAs/n^{++}GaAs tunnel junction, the reflectance is also important in this tunnel junction, as shown in Figure 6.

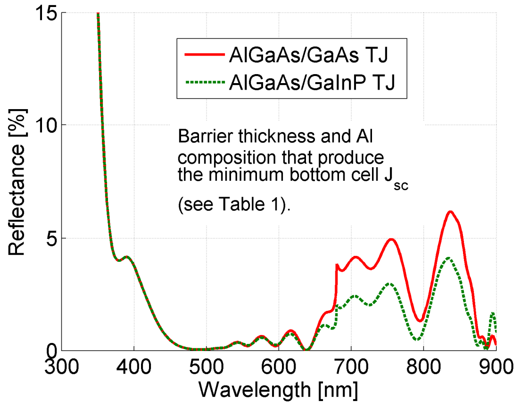

Figure 6. Calculated spectral reflectance of the structure shown in Figure 2, for the cases of barrier layers properties that produce the minimum bottom cell J_{sc}, according to the data shown in Table 1.

Concerning the bottom cell J_{sc} gain achieved when optimizing the barrier layers properties, it was found to be 0.46 and 0.33 mA/cm^2, for the p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions, respectively. The reason why this gain is lower in the high band gap tunnel junction is because it is easier to achieve a smoother refractive index contrast using AlGaAs and GaInP than using AlGaAs and GaAs. This leads to a higher interference-related reflectance in the p^{++}AlGaAs/n^{++}GaAs tunnel junction, as shown in Figure 6.

It must be reminded that the J_{sc} calculations have been carried out assuming a bottom cell minority carrier collection efficiency equal to unity. For a real minority carrier collection efficiency, the results obtained can differ, specially in the shape of the contour plots shown in Figure 5. This is so because the quantum efficiency (*QE*) of the subcell, directly related to its J_{sc}, can vary along the photon wavelength range of interest for the subcell (from 600 to 880 nm in the case of our GaAs bottom cell), due to a different collection efficiency in each layer which compose the subcell. Consequently, the modifications in the shape of the reflectance produced as the barrier layers properties are modified, give rise to a different modification of the *QE* than in the case of an ideal collection efficiency. Explained from a different point of view, the *QE* can be seen as the aggregate of light transmission, absorption, and carrier collection efficiency. The effect of modifications in the shape of one of these functions (the light transmission in our case) on the *QE* will depend on the actual shape of the rest of functions (the collection efficiency). A similar reasoning applies for the case of using a different solar spectrum than the AM1.5d ASTM-g173.

6 SUMMARY AND CONCLUSIONS

The theoretical analysis of the effect of the thickness and Al composition of the AlGaAs barrier layers taking part in p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions have shown that the interference-related reflectance inside the GaInP/GaAs dual-junction solar cell semiconductor structure analyzed, and the associated optical loss, is not negligible. A wide tolerance was found to exist to modifications in the value of the parameters of one barrier layer, around the calculated optimum case, without significant changes in the bottom cell J_{sc}. However, a strong cross-relation exists between the effect of variations in one barrier on the bottom cell J_{sc}, with respect to the actual characteristics of the other barrier layer.

When sweeping the parameters of the barrier layers along practical value ranges, the calculated bottom cell J_{sc} was found to exhibit an absolute variation of 0.43 and 0.33 mA/cm^2 for the p^{++}AlGaAs/n^{++}GaAs and p^{++}AlGaAs/n^{++}GaInP tunnel junctions, respectively, being the better coupling of refractive indexes in the latter the reason for a lower bottom cell J_{sc} variation. Despite the idealizations used in our calculations, this result illustrates the importance of a correct optical design of the semiconductor layers that compose a multijunction solar cell. A more advanced design, including other layers of the solar cell such as the top cell BSF and bottom cell window in the optimization, and using the actual optical parameters of the semiconductor layers grown in our laboratory, is ongoing.

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