
V.R. Cunha1,2*, R. M. S. Kawabata1,2, L. D. Pinto1,2, M. P. Pires2,3 and P. L. Souza1,2

1LabSem/CETUC, Pontifícia Universidade Católica, Rio de Janeiro, Brazil.
2DISSE-Instituto Nacional de Ciência e Tecnologia de Nanodispositivos Semicôndutores, PUC-Rio, Brazil.
3Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.
*e-mail: victorcunha@aluno.puc-rio.br

Keywords: Solar Cell, Comsol, AlGaInP

Abstract

The solar cells with highest efficiencies are the tandem cells with three or four $pn$ junctions in series, connected by tunnel diodes. The current produced by the stacked $pn$ junctions is limited by the smallest one. Therefore, to optimize the full solar cell efficiency it is crucial to match the current produced by the different junctions. This issue has been extensively investigated over the years. In the most usual case of three $pn$ junctions, the current is limited by the middle junction. Recently, the use of multiple quantum wells to further improve the current generated at the intermediate $pn$ junction was proposed. When such a middle junction is used, new optimization of the top cell is required to reach a better current matching. In this work we have used a commercial software, Comsol, to optimize the top solar cell for a triple junction structure to be used in space applications, meaning subjected to the AM0 spectrum. The newly designed solar cell is based on an InGaP $pn$ junction with AlGaInP n-doped window. The layers are lattice matched to GaAs and to Ge, which is the material used for the bottom $pn$ junction. These materials were chosen based on the fact that they are more resistant to radiation, which is of paramount importance for use in satellites. The first step to fabricate the designed solar cell is the optimization of each individual layer. The different InGaP and AlGaInP semiconductor layers of the designed solar cell have been grown by metalorganic vapor phase epitaxy at 675 °C. The alloys’ composition was calibrated. High doping levels of InGaP were achieved. However, difficulties in reaching a doping level of the AlGaInP window layer of around $1 \times 10^{18} \text{cm}^{-3}$, as required, were faced and should be discussed. Additionally, luminescence and x-ray diffraction data of the grown samples will be presented.

Introduction

The search for more efficient solar cells for space and terrestrial applications [1] raises much interest within the photovoltaic community around the world. William Shockley and Hans Queisser have demonstrated a theoretical limit [2] for the efficiency of different solar cells. Many ways to overcome this limit were proposed and have been tested over the years. Some of these alternatives are Intermediate Band Solar Cells [3], Quantum Well Multi-junction Solar Cells (QWMJSC) [4], among others. The conventional multijunction solar cell (MJSC) is one of these alternatives. The MJSC consists of two or more $pn$ junctions stacked with the goal to harvest a larger portion of solar spectrum. The MJSC has a great potential for achieving conversion efficiencies of over 40% [1].

The materials choice for the sub-cells needs to fulfill some requirements in order to compose the different junctions. The lattice parameter of the various materials should be matched to that of the substrate, the current on each cell should be as close as possible to those of the others and, in the case of spatial application, the materials should be resistant to high energy radiation.

In the triple junction solar cell, the bottom junction is usually Ge based, the central junction is made with GaAs and the top cell uses an InGaP junction. In this case, the current is limited by the middle GaAs junction. GaAs/InGaP multiple quantum wells are under investigation as a candidate for the middle junction material [1]. Additionally, they are more resistant to high energy radiation when compared to GaAs, being, in principle, more suitable for space applications. With the change in the characteristics of the central $pn$ junction, a new design of the top cell is required so that a better current match is achieved. In this work, we have addressed two issues, first we have simulated the InGaP top junction for space applications, which consists of a $pn$ junction of InGaP with a window and Back Surface Layer (BSF) of AlGaInP (quaternary material). Second, we have calibrated the AlGaInP growth by Metalorganic Vapor Phase Epitaxial deposition (MOVPE) for application as both window and BSF layers. The quaternary alloy is an attractive material for solar cell applications as an optical window in solar cells [6] where efficiencies larger than 40%[7] have been obtained due to the...
bandgap tunability of the quaternary alloy while being lattice-matched to GaAs.

Simulations

Simulations were performed using the semiconductor module that solves the Poisson and the continuity equations for electron and hole drift-diffusion currents using the finite element method. Different outputs are possible such as $J_xV$ curves, Band Diagram, Electric Field, among others. The simulations were made using the extraterrestrial solar spectrum (AM0).

First, simulations varying the thicknesses of the different layers were made. Many configurations were tested and two of them, named A and B, which maximize the efficiency of the device, are depicted in figures 1 and 2. Their following figures of merit are shown in Table 1: short circuit current ($J_{sc}$), open circuit voltage ($V_{oc}$), fill factor ($FF$) and efficiency.

<table>
<thead>
<tr>
<th>Contact</th>
<th>n = 1x10^16 cm^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlGaInP</td>
<td>20 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>80 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>750 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>300 nm</td>
</tr>
<tr>
<td>AlGaInP</td>
<td>30 nm</td>
</tr>
<tr>
<td>GaAs</td>
<td>300 nm</td>
</tr>
</tbody>
</table>

Figure 1. Structure configuration of A.

<table>
<thead>
<tr>
<th>Contact</th>
<th>n = 2x10^17 cm^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlGaInP</td>
<td>20 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>100 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>750 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>200 nm</td>
</tr>
<tr>
<td>AlGaInP</td>
<td>50 nm</td>
</tr>
<tr>
<td>GaAs</td>
<td>300 nm</td>
</tr>
</tbody>
</table>

Figure 2. Structure configuration of B.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{sc}$ (mA/cm²)</td>
<td>15,97</td>
<td>15,82</td>
</tr>
<tr>
<td>$V_{oc}$ (V)</td>
<td>1.38</td>
<td>1.17</td>
</tr>
<tr>
<td>$FF$ (%)</td>
<td>0.903</td>
<td>0.903</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>16.867</td>
<td>14.19</td>
</tr>
</tbody>
</table>

Table 1. Figures of merit for configurations A and B.

Four doping configurations were tested for the two best structures (A and B). They are named 0, 1, 2 and 3. Configurations 0 and 2 are the doping levels used in the original simulations of structures A and B shown in Figures 1 and 2. Configurations 1 and 3 are two other sets of doping level trials.

<table>
<thead>
<tr>
<th>Contact</th>
<th>n = 1x10^16 cm^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlGaInP</td>
<td>20 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>100 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>750 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>200 nm</td>
</tr>
<tr>
<td>AlGaInP</td>
<td>50 nm</td>
</tr>
<tr>
<td>GaAs</td>
<td>300 nm</td>
</tr>
</tbody>
</table>

Figure 3 and 4 show the $J_xV$ curves of structures A and B, respectively, for the four different doping configurations used.

Figure 3. $J_xV$ curves for structure A with four different doping configurations.

Figure 4. $J_xV$ curves for structure B with four different doping configurations.

Figure 5 depicts the doping configuration 3, which led to the maximum efficiency for both A and B structures. The new figures of merit using this doping level are shown in table 2.

<table>
<thead>
<tr>
<th>Contact</th>
<th>n = 2x10^17 cm^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlGaInP</td>
<td>20 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>100 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>750 nm</td>
</tr>
<tr>
<td>InGaP</td>
<td>200 nm</td>
</tr>
<tr>
<td>AlGaInP</td>
<td>50 nm</td>
</tr>
<tr>
<td>GaAs</td>
<td>300 nm</td>
</tr>
</tbody>
</table>

Table 2. Figures of merit for configurations A and B using the optimal doping levels of set 3.

The optimization process requires the right combination of materials’ parameters. We were looking for a configuration of thicknesses and doping levels which would give the maximum...
efficiency and match the current of the middle junction.

The purpose of the window layer is to be transparent to most of the solar spectrum so that the radiation is absorbed in the junction material, far from the surface, reducing the surface recombination velocity. A compromise exists concerning the thickness of this layer. It should not be too large to avoid absorption in this area as much as possible and should not be too thin either to maintain the pn junction as far as possible from the surface.

The behavior of the thicknesses in the active layers is different. The n-layer thickness shows better results when thinner but the p-layer behavior should be thicker for better results. The difference in behavior is related to the diffusion length which is related to the mobility and lifetime of the minority carriers.

When the pn junction is under illumination, the photogenerated current depends on the distance the electron hole pair has to travel to be swept by the electric field. The n-layer is highly doped and this affects directly the diffusion length so it is better to be thinner. On the other hand, as the p-side doping level is lower than the n-side the diffusion length of the minority carrier is greater. Note that electrons have mobility, lifetime and diffusion length greater than the holes do, thus, in order to increase the volume of the absorbing material, it is preferable to increase the thickness of the p-side of the junction.

The BSF consists of a doped region with a higher donor concentration at the rear surface of the solar cell. The interface between the high and low doped regions behaves like a pn junction itself and an electric field forms at this interface which introduces a barrier for the minority carrier to flow to the rear surface, forcing the electrons to move to the top of the cell which, consequently reduces the carrier losses. The presence of BSF is very helpful to raise the solar cell efficiency, however, its thickness does not play a major role in the device’s figures of merit.

The resistance of the solar cell is correlated with the thickness and doping of the different layers. Increasing the thickness raises the resistance and this factor is also taken into account to determine the figures of merit. The series resistance of a solar cell also depends on the semiconductor-metal contact. The optimal doping configuration obtained presents a higher doping level of the layers which are in contact with the metal layers (see figure 5), reducing the contact resistance.

**Window Layer**

The AlGaInP window layer was grown by MOVPE at 675°C. This temperature was chosen because it is the same as that used for growing the preceding InGaP layers. The samples were grown on a p-GaAs substrate. To work as a window layer an energy gap more than 60 meV larger than that of the InGaP (Eg=1.85eV) active region is expected so that it is essentially transparent to most of the solar radiation. Additionally, a doping level of about $10^{18}$ cm$^{-3}$ is required and the layer should be lattice matched to the substrate to avoid morphological defects.

The characterization techniques used were photoluminescence (PL), Hall measurements and x-ray diffraction.

Two undoped and two doped AlGaInP samples were grown and are named undop1, undop2, dop1 and dop2. The dopant source used was SiH$_4$. The main difference between the two undoped samples is the V/III ratio used for the growth, the V/III ratio used for undop2 being larger than that used for the undop1 sample. The same applies to the doped samples. They were grown with the same dopant flow but with different V/III ratios. Table 3 shows the growth conditions of the four samples.

![Figure 6. X-ray spectrum of the sample undop2.](image)

![Figure 7. X-ray spectrum of the sample dop2.](image)

Figures 6 and 7 show the x-ray diffraction spectra of samples undop2 and dop2, where one notices that the introduction of doping leads to an increase in mismatch of 709,1 ppm. Using the Matthews’ and Blakeslee’s model we obtain that the critical thickness is much higher than the thickness that will be used[8]. The increase in mismatch is revealed by a shift of the secondary peak to the right, meaning that the doped
structure has less In than the undoped does. The same trend is observed for samples undop1 and dop1.

The quaternary’s composition was estimated using results of PL together with those of x-ray diffraction. In figures 6 and 7 the peak of the alloy is shown on the right of the primary GaAs substrate peak, meaning that the layers are In poor, requiring more In to reach the lattice match condition. The obtained quaternary compositions are shown in Table 3.

Figure 8 shows the PL spectra of the samples.

![Photoluminescence spectra of samples undop1, undop2, dop1 and dop2 at room temperature.](image)

**Table 3.** Figures of merit using new doping level

<table>
<thead>
<tr>
<th>#</th>
<th>Composition</th>
<th>PL(RT)</th>
<th>Dopant Flow (sccm)</th>
<th>V/III</th>
<th>Lattice constant(Å)</th>
<th>Doping (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>undop1</td>
<td>A₀.₀₉Ga₀.₄₂In₀.₄₉P</td>
<td>2.03 eV</td>
<td>--</td>
<td>157,5843</td>
<td>5,649</td>
<td>undoped</td>
</tr>
<tr>
<td>undop2</td>
<td>A₀.₀₂Ga₀.₅₀In₀.₄₈P</td>
<td>1.₉₆ eV</td>
<td>--</td>
<td>165,369</td>
<td>5,646</td>
<td>undoped</td>
</tr>
<tr>
<td>dop1</td>
<td>A₀.₁₅Ga₀.₃₇In₀.₄₉P</td>
<td>2.₀₆ eV</td>
<td>1.₀₂</td>
<td>1₅₃,₇₅₄₁</td>
<td>5,₆₅₃</td>
<td>5x1₀¹⁷</td>
</tr>
<tr>
<td>dop2</td>
<td>A₀.₀₆Ga₀.₄₆In₀.₄₇P</td>
<td>2.₀₂ eV</td>
<td>1.₀₂</td>
<td>1₆₅,₃₆₉</td>
<td>5,₆₄₃</td>
<td>2.₇x1₀¹⁸</td>
</tr>
</tbody>
</table>

In summary, various InGaP solar cell structures for the top cell of a multijunction solar cell for spatial operation were simulated and an optimal structure in terms of the full structure geometry and doping levels has been proposed.

The AlGaInP window layer of such structure with the composition, bandgap and doping level required has been obtained by MOVPE growth after a careful calibration procedure.

Additionally, the PL spectrum is affected by the introduction of doping, as observed in figure 8. Samples undop2 and dop2 were grown under the same conditions. However, according to the PL spectra, the transition energy for sample dop2 is larger than that of the undoped sample, meaning that there is possibly a larger incorporation of Al. This is consistent with the fact that the sample is In poorer, as revealed by the x-ray diffraction spectrum and mentioned before. Again the same trend is detected for samples undop1 and dop1.

Now comparing the n-doped samples, we notice a five times larger efficiency in the doping for sample dop2 compared to sample dop1, although both were grown with the same SiH₂ dopant flow. This effect can be understood because a higher V/III ratio, used to grow sample dop2, leads to more sites III available for the donor, increasing the free electron concentration determined by Hall measurements.

### Conclusion

In summary, various InGaP solar cell structures for the top cell of a multijunction solar cell for spatial operation were simulated and an optimal structure in terms of the full structure geometry and doping levels has been proposed.

### Acknowledgments

The authors would like to thank the financial support from CAPES, FINEP, FAPERJ and CNPq and Professor Marco Aurélio Pacheco and CBPF for the use of the Comsol software.

### References