**Contribution of the Doping of the Lower Window Layer to Improve the Performances of the Tandem Solar Cell**

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**ABSTRACT**

Each layer of the tandem solar cell, its doping or its thickness, plays a primary task in improving the conversion efficiency. The optimization of the doping of the window layer of the lower solar cell of the tandem cell contributes to the reduction of the cost of the manufacture of its cells. The objective of this work is to show the role of doping the lower window layer on the performances of tandem CS in InGaP / GaAs with a tunnel heterojunction. For this a simulation is carried out using the Atlas-Silvaco simulator. It is specially designed for 2D and 3D modeling of components based on the physics of semiconductors, including electrical, optical and thermal properties. The adapted structure is essentially composed of an upper cell in InGaP and a lower cell in GaAs. Between the two upper and lower cells, there is a heterojunction tunnel) P ** N **. The structure studied is composed of a thin window layer heavily doped with the material \( \text{In}_{0.629}\text{Al}_{0.159}\text{Ga}_{0.371}\text{P}_{0.841} \). Our simulation showed that, for an illumination of AM 1.5 and at room temperature, the parameters, such as the short-circuit current and the conversion efficiency, improve with the doping of the upper window layer. The best conversion efficiency is 24.2343% for a doping of 8x1018 cm-3.

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**Keywords:**
- Window
- Performances
- Tandem
- Doping
- Solar cell

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**I. Introduction**

The manufacture of multi-junction solar cells is done almost exclusively with III-V materials, which permits an optimal exploitation of the solar spectrum by the diversity of their band gap energy and by their optoelectronic properties. Multispectral conversion is done by stacking several materials whose gap energies decrease from top to bottom. What gives the probability of using a wide range of solar spectrum is to expect high conversion yields [1]. The first of the tandem cells consisted of a layer of molecules evaporated for the first cell and a polymer layer deposited in the wet region for the second [2]. These cells are based on III-V materials that have been developed since the sixties [3]. The III-V materials are bodies composed from an element of column III and an element of column V of the periodic table of Mandilive. The choice of materials for the solar cell tandem depends on certain parameters such as, the width of the bandgap, the lattice constant and the absorption coefficient. III-V materials have energy as promising for solar cells due to their direct bandgap which covers almost the solar spectrum [4].

Optimizing the performance of these structures consists of finding optimal technological parameters like the conversion efficiency, short circuit current density and open circuit voltage. The main parameters to optimize in the solar cell tandem, or solar cell multijunction CSMJ, are thickness and its level of doping of each layer. The major problem is the large number of parameters that influence performance. Simulation provides a relation between the experimental world and the theoretical world, it complements theory and the experimental and builds physical reality. Numerical simulation has been an important tool in optimization of tandem solar...
cell designs. The simulation of devices semiconductor has become more and more used in recent years. Several calculation and simulation software have been developed by the research community in this area. As an example, we can cite: PC-1D, AFORS-HET, ASA, ASPIN, AMPS-1D and SCAPS-1D.

Among the software that effectively simulates the behavior of semiconductor devices is Silvaco (Silicon Valley Societe) [5]. This is achieved by numerically solving the Poisson equation and the equation continuity of charge carriers in two-dimensional n a finite number of points forming the mesh of the structure defined by the user or by the program [6]. The results obtained by the simulation of tandem solar cells, which aim to optimize manufacturing parameters such as thickness, number of layers and doping, can be used to minimize the manufacturing cost of these cells.

The objective of this work is to show the role of doping of the lower solar cell window layer on the performances of the tandem solar cell with a tunnel heterojunction. The solar cell used is a tandem solar cell with an InGaP / GaAs junction. After finding the doping of this layer which will give the best conversion efficiency. To do this, a simulation is realized using the Atlas-Silvaco software

II. Structure of the Solar Cell

The solar cell to be simulated is a tandem solar cell with an InGaP / GaAs junction (heterojunction). The adapted structure is essentially composed of an upper cell (In0.49 Ga0.51P/In0.49 Ga0.51P) and a lower cell (GaAs/GaAs). Between the two upper and lower cells, there is a junction tunnel (homojunction or heterojunction) P ++ N ++ (InGaP/GaAs) for the role of the connection between the two cells (Fig 1).

![Diagram of Tandem Solar Cell](image-url)

**Anode**

- 0.03 μm window (P-In0.49Al0.51Ga0.2P) P=2x10^{18}
- 0.05 μm emitter (P-In0.5 Ga0.5P) P=2x10^{17}
- 0.55 μm base (N-In0.49 Ga0.51P) N=7x10^{16}

**BSF**

- 0.03 μm BSF (N-In0.49Al0.51Ga0.2P) N=2x10^{18}
- 0 to 0.032 μm tunnel (N-In0.49 Ga0.51P) N=1x10^{17} to 1.5x10^{17}
- 0 to 0.032 μm tunnel (P-GaAs) P=2x10^{19}
- 0.04 μm window (P-In0.5 Ga0.5P) P=2x10^{18}
- 0.5 μm emitter (P-GaAs) P=2x10^{18}
- 2 μm base (N-GaAs) N=2x10^{17}

**Cathode**

- 0.1 μm BSF N-Al0.2Ga0.8As N=5x10^{11}
- 0.2 μm SUBSTRAT (N-GaAs) N=1x10^{13}

Figure 1 : Tandem solar cell structure used [7]

Usually, these tandem solar cells use GaAs / GaAs tunnel junction, i.e. a homojunction. But in this work we used a tunnel junction in InGaP / GaAs, that is to say a heterojunction tunnel. [8]

II.1. Window Layer

The window layer is a conductive layer. It allows electrons to flow to the electrical contacts without increasing the series resistance of solar cell. The material used must meet the following requirements:

- It must have a mesh parameter close to the emitter’s mesh parameter. [8]
- It gap must be greater than the gap of emitter. [9]
- It must have a wide valence band offset from the emitter, to create a strong potential barrier for minority holes.
- Its concentration must be greater than 10^{18} cm^{-3}.
- Material must be of high quality to minimize surface recombination.
In this work, we use the material $\text{In}_{0.629}\text{Al}_{0.159}\text{Ga}_{0.371}\text{P}_{0.841}$ in the upper window and $\text{In}_{0.49}\text{Ga}_{0.51}\text{P}$ for the inner window of the tandem solar cell.

II.2. Properties of the Material used in the Upper Window

Knowledge of the electronic and optical properties of all III-V alloys composing tandem solar cells is also a major challenge for the development of the photovoltaic device. For our material $\text{In}_{0.629}\text{Al}_{0.159}\text{Ga}_{0.371}\text{P}_{0.841}$ which is used in the construction of the upper window, the main parameters are given below:

1) Band Diagram

Figure 2 illustrates the energy band structure of a front window layer coupled to a p-n homojunction (Figure 1(a), then of a p-n homojunction coupled to a rear window layer (Figure 2(b)).

![Figure 2: Window layer (a) front et (b) back [10]](image)

In the figure 2: the $E_f$ is a spatially independent reference energy known as the Fermi. The conduction and valence bands, whose energy minimum is located at energies $E_c$ and $E_v$ respectively.

2) Main Parameters

The main parameters which characterize the material $\text{In}_{0.629}\text{Al}_{0.159}\text{Ga}_{0.371}\text{P}_{0.841}$ such as $E_g$, $a$, $X$, and $\varepsilon_r$, are given in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ (eV)</td>
<td>2.23</td>
</tr>
<tr>
<td>$a$ (A)</td>
<td>5.68</td>
</tr>
<tr>
<td>$X$ (eV)</td>
<td>4.01</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Where $X$ is the electron affinity of the semiconductor material, $E_g$ is the bandgap, $a$ is the lattice constant and $\varepsilon_r$ is relative permittivity.

III. Atlas-Silvaco Software

SILVACO is a company that specializes in the development of simulation software targeting almost all aspects of modern electronic design. The diagram of the inputs and outputs are given in Figure 3.
There are five groups of commands, these groups must be organized correctly (Fig 4).

The simulation is based on inputs and outputs. The inputs are made, first of all, the specification of the structure which is based on a very precise mesh, the determination of each region and the location of the electrodes. The type and level of doping are also defined. The Atlas-Silvaco tool is used to define the dimensions of the simulated structure, the parameters of the doped zones (location, type, level and doping profile), to place the electrical contacts on the structure and to define the mesh [11].

III.1. Model

The introduction of the adopted physical models leads to a good simulation of the structure. It is therefore essential to introduce the appropriate parameters in physical models. The choice of models depends on the materials chosen for the simulation and their environment and dimensions.
The Atlas-Silvaco could be used to simulate our structure. The template declaration syntax is as follows:

\[
\text{MODELS <model flag><general parameter><model dependent parameters>}
\]

In this work, the models concerned are optical generation, mobility and recombination model.

1) Optical Generation Model

The incident illumination corresponds to the 1M1.5 spectrum. The wavelengths of the absorbed photons range from 0.305 to 3.455 µm. It is introduced into the Atlas-Silvaco program by the instruction:

\[
\text{BEAM x.o=0.5 y.o=0.5 angle = 90 wavel.start=0.305 wavel.end=3.455 wavel.num=0.305}
\]

2) Recombination Models

The latter often consists of three types: SRH recombination (Shockley-Read-Hall) radiative recombination and Auger recombination (equation (2) [14]. Total recombination is the sum of these three types.

\[
R_{SRH} = \frac{p_n n_i}{\tau P_0 (n + n_i e^\frac{E_{tr}}{kT_L}) + \tau p_0 (p + p_i e^{-\frac{E_{tr}}{kT_L}})}
\]

Where \(E_{tr}\) is the difference between the trap energy level and the intrinsic Fermi level, \(T_L\) is the lattice temperature in degrees Kelvin and \(T_{N0}\) and \(T_{P0}\) are the electron and hole lifetimes.

\[
R_{AUGER} = AUG_N (p_n^2 - n_n^2) + AUG_P (n_p^2 - p_p^2)
\]

Where the model parameters \(AUG_N\) and \(AUG_P\) are user-definable in the MATERIAL. You can activate this model with the AUGER parameter from the MODELS statement.

The rest of the constants are given in the table 2[5]:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_{n0}) (s)</td>
<td>1 × 10^{-7}</td>
</tr>
<tr>
<td>(\tau_{p0}) (s)</td>
<td>1 × 10^{-7}</td>
</tr>
<tr>
<td>(E_{tr}) (eV)</td>
<td>0</td>
</tr>
<tr>
<td>(AUG_N \left(cm^6/s\right))</td>
<td>8.3 × 10^{-3}</td>
</tr>
<tr>
<td>(AUG_P \left(cm^6/s\right))</td>
<td>8.3 × 10^{-3}</td>
</tr>
</tbody>
</table>

3) Mobility Model

With this model, the mobilities of the electrons \(\mu_n\) and of the holes \(\mu_p\) are calculated using the following formulas (equation (3) and (4)):

\[
\mu_{n0} = MUN \left(\frac{T_L}{300}\right)^{-TMUN}
\]

\[
\mu_{p0} = MUP \left(\frac{T_L}{300}\right)^{-TMUP}
\]

The low field mobility parameters: \(MUN\), \(MUP\), \(TMUN\) and \(TMUP\) can be specified in the MOBILITY statement. The constants are given in table 3.
4) Tunnel model

Three types of tunnel effect were used in the simulation:
- Inter-band tunnel.
- Intra-band tunnel

IV. Results

To study the influence of the doping of the window layer of the lower cell d on the photovoltaic characteristics of the cascade solar cells studies we fixed the optimal thickness and we chose a range of electron doping concentration between 2x10^{19} and 8x10^{19} cm^{-3} for the window layer.

The first solar cell is simulated without the window layer of the upper cell. The values of the parameters are given in the table 4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUN(Cm²/Vs)</td>
<td>1000</td>
</tr>
<tr>
<td>MUP(Cm²/Vs)</td>
<td>500</td>
</tr>
<tr>
<td>TMUN</td>
<td>1.5</td>
</tr>
<tr>
<td>TMUP</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The second solar cell is simulated with a window layer of the upper cell. The variations of the parameters I_{sc}, V_{co}, FF and \eta depending on the doping are given in the following graphs:

The effect of doping the window of the lower cell is presented in figures 5 (a) (b) (c) (d)
In the first zone (I): there is a significant increase in efficiency with doping, this phenomenon is due to the increase in electron-hole pairs. In the second zone (II): there is a proportional increase in the yield as a function of the variation in doping compared to the increase in the first zone. It is noted that the increase in the doping level of the window allows a remarkable improvement in the conversion efficiency of the structure. So according to the figure also, the current receives an unexplainable change between $1 \times 10^{19}$ and $2 \times 10^{19}$ cm$^{-3}$. For the three other parameters, such as the open circuit voltage, the form factor, and conversion efficiency, their increase is due to the reduction of the resistance and the diminution of the potential barrier.

For the tandem second solar, with a window layer to the upper solar cell, the optimal values are given in the table 5. These values are obtained for a doping level of $8 \times 10^{18}$ cm$^{-3}$

<table>
<thead>
<tr>
<th>$I_{sc}$ (mA)</th>
<th>$V_{oc}$ (V)</th>
<th>$FF$ (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1436</td>
<td>2.42117</td>
<td>91.2450</td>
<td>24.2343</td>
</tr>
</tbody>
</table>

**III. Conclusion**

The window layer is used to minimize reflection losses. The conversion efficiency obtained for the tandem solar cell without the window layer of the lower cell is around 22.1823%. And for the same cell and with a window layer the yield amounts to 24.2343%. The conversion efficiency reaches its maximum value stabilizes from the value of $8 \times 10^{18}$ cm$^{-3}$, then this is the optimal doping of the window layer of the lower cell. In conclusion, we have shown that the window layer of the upper cell has a considerable advantage over the energy efficiency of the tandem solar cell.

**References**


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