Proposal of Si and GaAs Double Junction Solar Cell: Characterization and Simulation.

W M M Bazilio[1*], R M S Kawabata[1], G M Torelly[1], P L de Souza[1], R F Calili[2] and D R Louzada[2]

[1] Department of Electrical Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro,RJ, 22451-900, Brazil

[2] Postgraduate Programme in Metrology, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro,RJ, 22451-900, Brazil

willian.m.bazilio@aluno.puc-rio.br

Abstract. Integrating III-V solar cells with silicon (Si) holds great promise for advancing commercial solar cell technology. Various methods exist to combine III-V and silicon, each presenting unique obstacles. Our study focuses on different III-V solar cell configurations to enhance their compatibility with silicon cells. Utilizing the SCAPS software, we conducted simulations to design an ideal III-V device that closely aligns with commercially available Si solar cells. By optimizing the base layer's thickness (2,5 µm) and doping level during the simulations, we achieved an impressive efficiency of 28.03%.

1. Introduction

In solar photovoltaic energy generation, there are a great interesting the development of new technologies that enhance the photovoltaics' cells. This is even more important when we consider both the growing necessity for clean energy and the efficiency's limits of now-a-day silicon (Si) cells. In this scenario, the coupling of III-V semiconductors and Si has been of great interest in optoelectronics due to the potential benefits of exploiting both material's strengths.

The combination of III-V materials with Si presents several advantages, with the main one being the fact that III-IV semiconductors have a high photon absorption efficiency (due to their high crystal quality and bandgap configuration), while Si semiconductors have a low manufacturing/ production cost, due to the technology maturity and existing large-scale production infrastructure.

The concept of photovoltaics using III-V materials on Si substrates has been known since the 1980s [1-2]. This approach involves the use of III-V semiconductors with high crystalline quality to develop solar cells with high energy conversion efficiency. However, the production costs associated with this technology have limited its widespread use, relegating it to niche applications like satellites.

To address the cost issue, attempts have been made to grow III-V solar cells directly on Si substrates. However, these attempts have not been very successful so far. The main challenge lies in the significant

differences in lattice constants and thermal coefficients between III-V materials and Si. These differences can lead to defects and limitations in the performance of the solar cells.

Additionally, the record efficiency for Si solar cells has only improved 0.6 % in 15 years, while III-V solar cells gained 1 % efficiency per year in the same period. Therefore, different approaches to couple III-V photovoltaic cells to silicon have attracted much investment, since it has potential to combine high efficiency with low cost.

Despite the challenges, researchers continue to explore and develop techniques to overcome the obstacles and make III-V on Si photovoltaics more viable for large-scale solar energy applications.

In this work, we chose the stacking approach to couple III-V with Si solar cells. We present characterization results of Si solar cells produced at Pontifícia Universidade Católica do Rio Grande do Sul (PUC-RS) and simulation results of a III-V solar cell to be grown at Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), which should be later stacked with the investigated Si cells.

The present work is structured with the first section comprising this introduction, section 2 presents the methodology used. The results and discussions are presented in section 3, and in section 4, the conclusions of the work are drawn.

2. Methodology

The work was divided into two stages: Experimental Testing and Simulation. In the following, each of the two stages will be described in detail.

2.1. Simulation

Modelling of the hybrid solar cell composed of an upper layer of GaAs and a lower layer of Si was conducted. Figure 1(a) illustrates the four-terminal configuration for integrating the III-V and Si solar cells. This methodology involves the utilization of a transparent insulating adhesive to stack both cells together. Finally, the layers in the GaAs solar cell are depicted in Figure 1(b).

(a) (b)

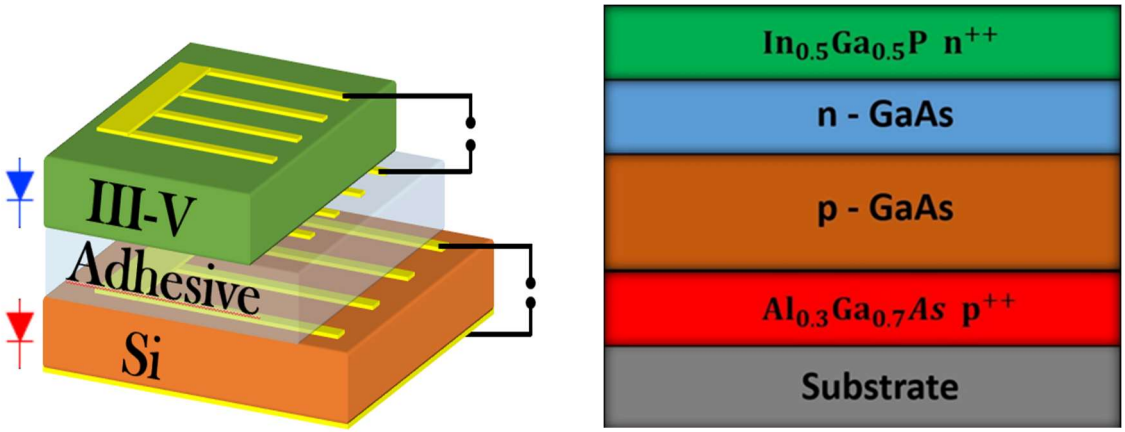

Figure 1 – (a) Schematic of a tandem III-V on Si solar cell coupled with a transparent insulating adhesive and (b) layer structure of the GaAs cell.

The top GaAs solar cell was simulated with the Solar Cell Capacitance Simulator (SCAPS) software [3], aiming to identify a suitable III-V structure to be integrated with the bottom Si solar cell. Initially, GaAs solar cells with different active layer thicknesses were analysed to assess their performance.

The SCAPS software provides essential I-V characteristics of the device, from which key figures of merit such as efficiency (E_{ff}), short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and maximum extracted power (P_{max}) is derived.

The software provides the I-V characteristics of the device, enabling the extraction of key figures of merit, including efficiency (E_{ff}), short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and maximum extracted power (P_{max}).

In Table 1, the physical characteristics of the two solar cells (Si and GaAs) are presented, while Table 2 describes the electrical characteristics of each layer associated with the two solar cells, which are necessary for the simulation of electricity generation.

Table 1 - Physical properties of the solar cells.

	Material	Layer	Thickness [µm]	Doplin [cm^{-3}]
Si	$Si:N^{+}$	FSF	0,03	1,00E+20
	Si:N	Front	15	1,00E+17
	Si:P	Bulk	200	2,00E+18
	$Si:P^{+}$	BSF	1	1,00E+20
GaAs	$In0,5Ga0,5P : N^{++}$	FSF	0,015	1,00E+19
	GaAs : N	Emissive	0,03	1,00E+19
	GaAs : P	Base	2550	9,00E+18
	$Al_{0,3}Ga_{0,7}As : P^{++}$	BSF	1	4,00E+18

Table 2 – Electrical proprieties of each layer associated with the two solar cells.

Parameter	Si	GaAs	$In_{0,5}Ga_{0,5}P$	$Al_{0,3}Ga_{0,7}As$
BandGap [eV]	1120	1424	1760	1798
Electron Affinity [eV]	4500	4070	4090	4100
Dielectric Permititivity	11900	12900	11800	11000
Electron Thermal Velocity [cm/s	1.00E+07	4.40E+08	4.40E+10	3.77E+08
Hole Thermal Velocity [cm/s]	1.00E+07	1.80E+08	1.80E+10	1.65E+08
Electron mobility [cm^2/s]	1.50E+07	4.00E+09	8.00E+05	2.00E+06
Hole mobility [cm^2/s]	4.50E+00	5.00E+04	3.50E+04	1.38E+06

Given that the program's objective is to simulate a realistic solar cell, it considers not only the parameters associated with the material structure but also various factors, such as temperature, series resistances, solar spectrum, and surface transmission. However, it is important to emphasize that the SCAPS software does not calculate surface reflection. Nevertheless, it allows users to input the spectrum for analysis.

According to the literature [4], GaAs, which possesses a 1.42 eV band gap, has been demonstrated as the optimal choice for a tandem cell with Si as the bottom sub-cell.

2.2. Experimental Testing

For the characterisation of the solar cells, an experimental setup was used consisting of a solar simulator (Sciencetech SF300A, London, ON, Canada) and a semiconductor parameter analyser (HP 4145B, Palo Alto, CA, United States). This setup allowed the measurement of the solar cell's current density-voltage (J-V) characteristic curve under 1(one) sun irradiance, facilitating the extraction of the relevant figures of merit (Jsc, Voc, FF, Pmax, Eff).

Figure 2(a) shows the Si solar cell of 4,03 cm^2 of area, bifacial PERT (Passivated Emitter Rear Totally diffused) in detail, and Figure 2(b) presents the cell being prepared to be tested under controlled light conditions.

(a) (b)

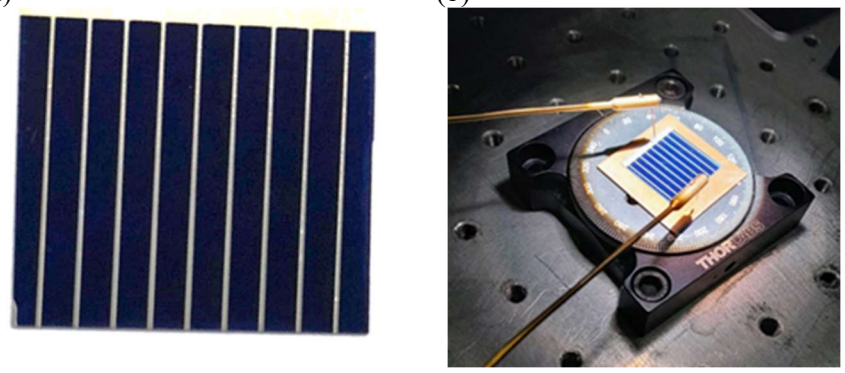

Figure 2 – (a) Si Cell in detail and (b) under one sunlight to be tested

As the GaAs Solar cell were not available, its experimental assay will be conducted on another occasion.

3. Results and Discussions

Determining the optimal thickness of the III-V sub-cell's base layer is crucial. To achieve this, we employed the SCAPS software for simulating the photo-generated current density while varying the p-base layer thickness. Figure 1(b) illustrates the schematic representation of the III-V sub-cell structure. The n-emitter layer's thickness remained constant at 0.030 µm, with doping levels of 1 x 1019 cm^{-3} and 9 x 1018 cm^{-3} for the n-emitter and p-base layers, respectively.

The simulation results are presented graphically in Figure 3. These results shed light on the impact of thickness on the figures of merit. As expected, an increase in current density is observed as the thickness ranges from 0.050 µm to 4 µm, owing to higher photon absorption. However, it is important to note that at a thickness of approximately 2.5 µm, the current density saturates. Hence, it is recommended to opt for a 2.5 µm thick base layer, which reduces material consumption while allowing a small portion of the high-energy spectrum to be absorbed by the bottom Si sub-cell.

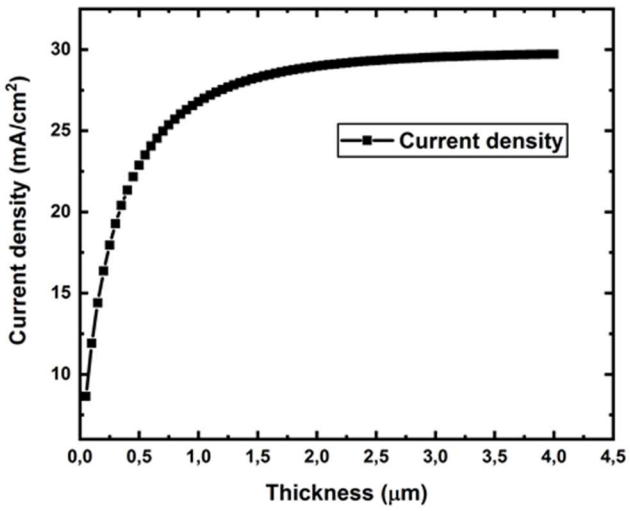

Figure 3 - Simulated current density as a function of the p-layer thickness for a pure GaAs solar cell.

Once the GaAs cell thickness was optimized through simulation, an experimental assay was conducted using the Si cell. The luminous intensity was varied to obtain Voltage and Current curves for different power levels (Figure 4).

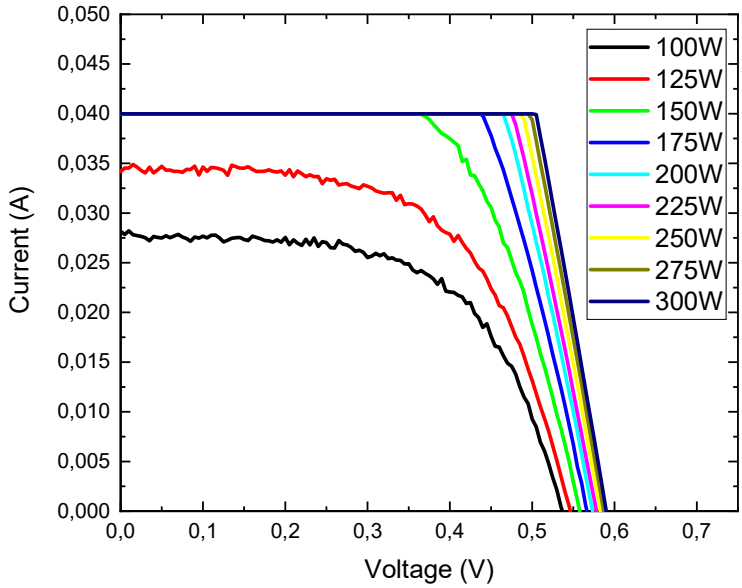

Figure 4 -I-V curve for a Si solar cell

It can be observed that as the power is increased, the electric current becomes saturated, making it impractical to conduct a detailed analysis. To address this issue, both the short-circuit (I_{sc})current and open-circuit voltages (V_{oc}) were measured for different power levels, ranging from 100 W to 300 W with a step of 25 W (Figure 5). In Figure 5(a), a linear relationship between current and power can be observed, whereas, in Figure 5(b), there is a linear relationship between voltage and power, albeit with a larger fitting error. The standard power for photovoltaic cell testing is the power of 300 W or the pawer relative to an irradiance of 100 mW/cm^2 for an air mass (AM) of 1,5.

(a) (b)

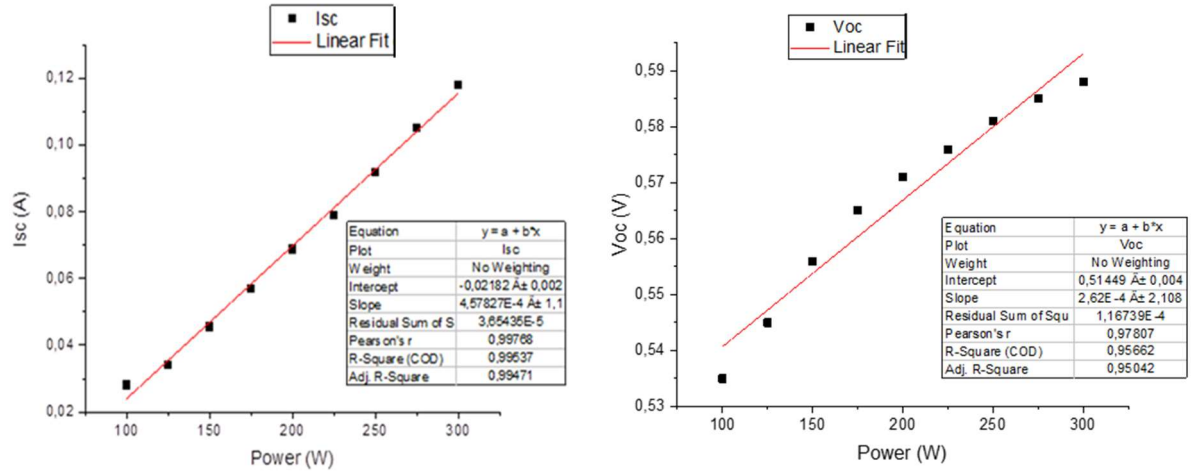

Figure 5 – (a) I X P Linear relationship and (b) V X P Linear relationship

Figure 6(a) depicts the graphic of the estimated (by measure) Si current density X Voltage, while Figure 6(b) presents the simulation of the current density X Voltage.

(a) (b)

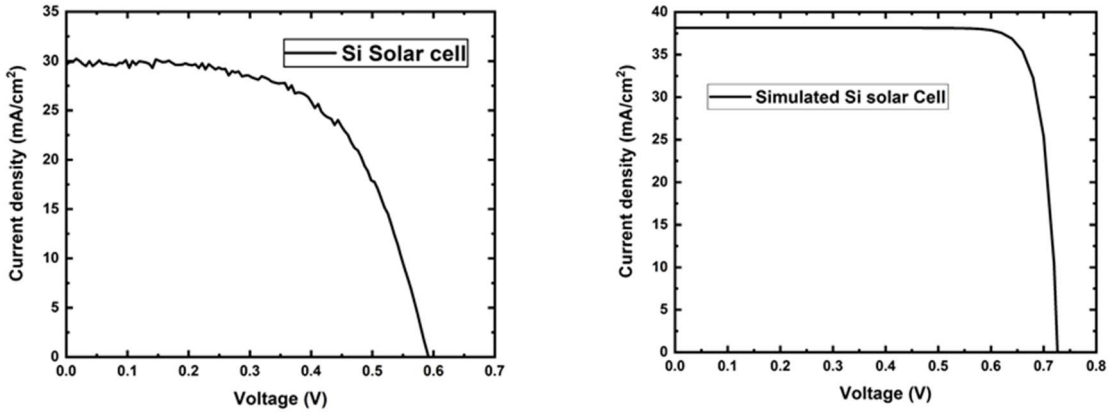

Figure 6 – (a) shows the current density X Voltage measured and (b) the current density X Voltage simulation.

Figure 7 shows the simulated J-V curve and the figures of merit for the GaAs sub-cell with a thickness of 2.55 µm. The results obtained in the performance study of the GaAs cell regarding the base layer thickness are similar to those presented in the work [5-6]. In Table 3, a summary of the figures of merit obtained through simulation and measurement is presented

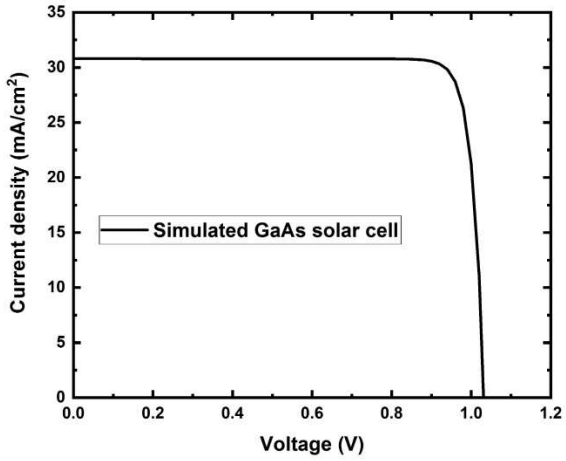

Figure 7 - Simulated J-V curve for a pure GaAs solar cell.

Table 3 – Results of simulation and measured Si solar cell and the simulated GaAs solar cell.

Figures os Merit	GaAs (Simulation)	Si (Simulation)	Si (Measured)	Error Si [%]
I_{sc} [mA/cm^2]	30,79	36,03	29,62	21,6
V_{oc} [V]	1,03	0,62	0,59	5,1
FF [%]	88,16	83,17	60,93	36,5
E_{ff} [%]	28,03	18,71	12,11	54,5

4. Conclusion

GaAs have been investigated as a Si tandem partner for a silicon solar cell. It was made a characterization the dual-junction cell was performed and simulation results indicate that a 2.5 µm thick GaAs p-type base layer should be used in the III-V sub-cell in a stacked configuration with Si as the bottom device.

Upon identifying the saturation issue for powers greater than 125 W, a procedure was conducted to estimate the Current (A) X Voltage (V) graphs of Si cells. This involved establishing linear relationships between Power (W) X Current and Power X Voltage.

The percentage errors between simulations and experimental tests in Si cells of 54.5% have been observed, indicating that adjustments to the simulation conditions need to be considered in order to ensure more realistic simulation outcomes.

For future work aiming for better coupling, simulations will be conducted with different emitter thicknesses and other III-V materials, such as InGaP, which has a higher energy gap than GaAs. The intention to simulate these materials is justified considering a better absorption of higher-energy photons, resulting in a higher Jsc. We will also simulate the complete structure in order to estimate the combined efficiency and compare it with that of the individual Si cell

Acknowledgments

This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel (CAPES) - Financing Code 001.

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