Investigation of an InGaN/Si-Based Heterojunction Tandem Solar Cell

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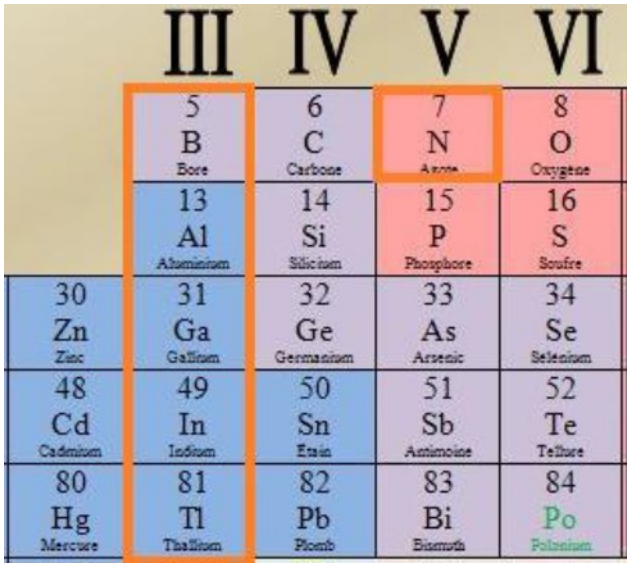
Abstract. This study explores the design and performance of a heterojunction tandem solar cell comprising Indium Gallium Nitride (InGaN) and Silicon (Si) layers. The integration of InGaN with Si aims to exploit the complementary absorption spectra of the two materials, thereby enhancing overall solar energy conversion efficiency. InGaN, with its tunable bandgap, serves as the top cell, effectively capturing high-energy photons, while the Si bottom cell absorbs the remaining lower-energy photons. Through detailed simulations and experimental evaluations, we demonstrate significant improvements in efficiency compared to traditional single-junction Si solar cells. The analysis includes optimization of the InGaN composition, thickness, and interface quality to minimize recombination losses and maximize current matching between the sub-cells. Our findings indicate that the InGaN/Si tandem configuration can achieve efficiencies exceeding 30%, showcasing its potential as a viable candidate for next-generation photovoltaic technologies. This research provides valuable insights into material selection, device architecture, and fabrication techniques critical for advancing high-efficiency solar cell development.

Keywords: Heterojunction, Tandem solar cell, Indium Gallium Nitride (InGaN), Silicon (Si).

1 Introduction

Semiconductor solar cells are fundamentally quite simple devices. Semiconductors have the capacity to absorb light and to deliver a portion of the energy of the absorbed photons to carriers of electrical current-electrons and holes. Thus, a solar cell is simply a semiconductor diode that has been carefully designed and constructed to efficiently absorb and convert light energy from the sun into electrical energy.

The GaN and InN binary materials and their ternary InxGa1-xN are semiconductors belonging to the category of nitrides of elements III, that is to say, compounds nitrogen and column III elements of Mendeleev's table, namely boron, aluminum, gallium, indium and thallium, Fig. 1. We will detail the morphological, structural, electrical and optical characteristics of these materials, and particular of InGaN.



	III	IV	V	VI
	5 B Bore	6 C Carbone	7 N Azote	8 O Oxygène
	13 Al Aluminium	14 Si Silicium	15 P Phosphore	16 S Soufre
30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Sélénium
48 Cd Cadmium	49 In Indium	50 Sn Etain	51 Sb Antimoine	52 Te Tellure
80 Hg Mercure	81 Tl Thallium	82 Pb Plomb	83 Bi Bismuth	84 Po Polonium

Fig .1: Partial periodic table [1].

III-V semiconductor materials are compound bodies formed from a column III element and one element of column V of the Mendeleev periodic table Fig.1, thus many binary, ternary and quaternary compounds can be made. The III-V compounds are of a well-defined class with properties that are sources of interest in terms of fundamental knowledge and applications.

The practical interest of the III-V semiconductors is further considerably enhanced by the possibility of making alloys by partial substitution of one of the elements of the same column. It is possible, for example, to obtain ternary alloys of the GaXAl1-X As, GaXIn1-XAs or quaternary type, such as GaXIn1-XAsY P1-y. Fig. 2 shows the variations of the band gap of the alloy as a function of the crystalline parameter, which itself varies with the composition. This diagram shows that it is possible to obtain materials whose band gap width, and therefore the optical properties, vary over a wide range. However, there is an important constraint for the manufacture of these materials, which are made in thin layers by epitaxial growth on a binary substrate: the crystalline parameter must be very close to that of the substrate. The diagram of the Fig. 1 makes it possible to know the composition of any ternary alloy that can be epitaxial in a thin layer on the GaAs or InP binary substrates [2].

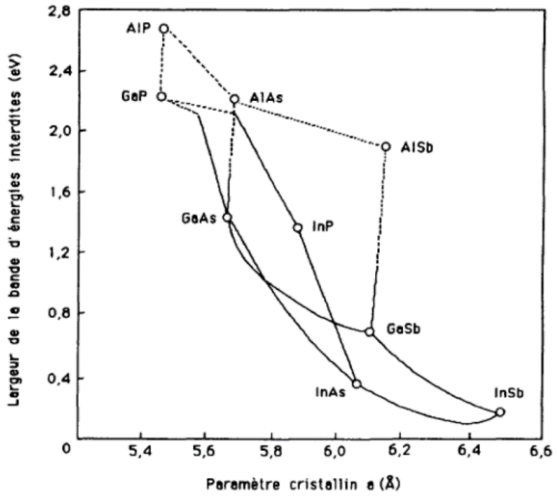


Fig. 2: Band gap width according to crystal parameter for alloys III-V [2].

These materials have a large gap and they can cover the entire solar spectrum from infrared to ultraviolet. They are characterized by a high absorption coefficient, high mobility and good mechanical and thermal resistance. In addition, they have a good resistance to strong electric fields and electromagnetic radiations from where the utility of used them in the space field. Among their applications the lasers, the detectors, the amplification of high power and the solar cells [3].
we present a detailed description of our study carried on a tandem solar cell, based on Indium Gallium Nitride (InGaN)/ Silicon (Si) heterojunction. The top sub-cell material is chosen to be $In_{0.57}Ga_{0.43}N$, which has a calculated band gap of $E_g=1.559\ eV$ corresponding to the maximum energy of the solar spectre AM1.5. The bottom sub-cell material is crystalline silicon with lower band gap of $E_g=1.08\ eV$. The cell is investigated under the standard global solar spectrum (AM1.5G) illumination with ~ 0.1 Watt/cm^2 total incident power density, and 300°K ambient temperature. The study is mainly by numerical simulation using, as a tool, the SILVACO-ATLAS software. This latter allows us to calculate the device performance parameters such as the current density-voltage and the power-voltage characteristics, (*J-V*) and (*P-V*) respectively, the short-circuit current density (J_{sc}), the open-circuit voltage (V_{oc}), the maximum power (P_{max}) delivered by the cell, the fill factor (FF), and the conversion efficiency (η)

2 Studied cell:

The studied cell Fig. 3 is a tandem based on InGaN/Si heterojunction with a total surface of 1 cm^2,exposed to the solar radiation AM1.5.The top sub-cell is based on InGaN material with the following regions: -0.01 µm of n-type GaN layer as an optical window (E_g=3.4 eV), heavily doped with $N_d=10^{20}cm^{-3}$- 0.01 µm of n-type In0.57Ga0.43N layer (E_g=1.559 eV) as an emitter, heavily doped with $N_d=10^{20}\ cm^{-3}$- 0.05 µm of p-

type In0.57Ga0.43N layer doped with $N_a=10^{16}$ cm^{-3}, as a base and -0.01 µm of p-type In0.57Ga0.43N layer, heavily doped with $N_a=10^{20}$ cm^{-3}. To model the interlayer between the two sub-cells, an electrode of 0.01 µm (ITO), which exactly overlay the interlayer, is added between the two sub-cells. With attaching a lumped resistance to it using the statement: contact name=com resist=1e16, we force the current to flow from Anode to cathode and prevent any current to flow in the added electrode. Physically it can be justified by the fact that interlayer is acting like a resistor letting current flows without significant limitation.
We note that a more physical approach, taking into account tunnelling conduction, could be used as well using the non-local band to band tunnelling (NLBBT) model.

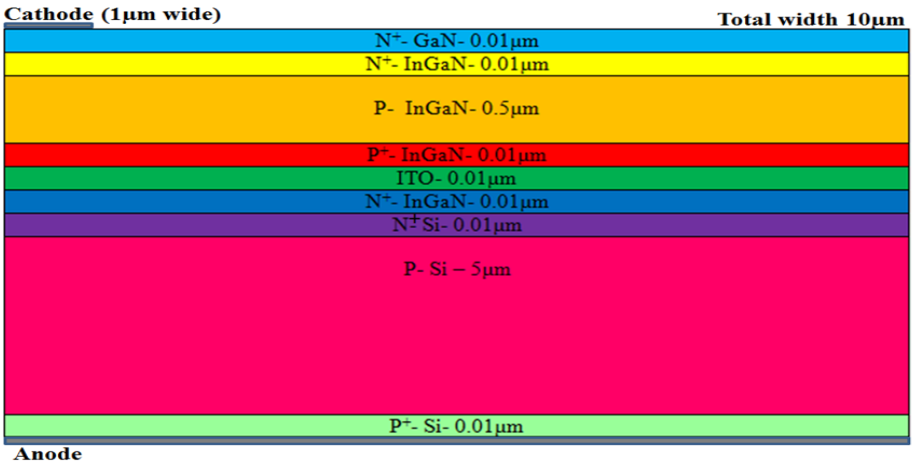


Fig. 3: structure of the studied InGaN/Si heterojunction tandem solar cell.

The bottom sub-cell is based on crystalline silicon (Si) material (E_g≅1.08 eV) with the following regions: -0.01 µm of n-type In0.57Ga0.43N layer heavily doped with $N_d=10^{20}cm^{-3}$-0.01 µm of n-type Si layer heavily doped with $N_d=10^{20}cm^{-3}$,as an emitter - 5µm of p-type Si layer doped with $N_a=10^{16}$ cm^{-3},as a base and -0.01 µm of p-type Si layer, heavily doped with $Na=10^{20}$ cm^{-3}. No material specification is imposed on electrodes. They are simply defined as cathode and anode on the top and the bottom of the device, respectively. The cathode covers only 1µm of the total wide of the cell (10µm) in the way that the majority of the front surface will be enlightened. The anode, however, cover the whole back surface.
The band gap combination of ~1.56 eV (In0.57Ga0.43N) and 1.08 eV (Si) is predicted to be optimal for a dual-junction tandem cell operating under the AM 1.5 solar irradiance [4].

Figs.4 and 5 show respectively the structure of the InGaN/Si heterojunction tandem solar cell as presented by the Silvaco-Atlas simulator and the applied spatial mesh.

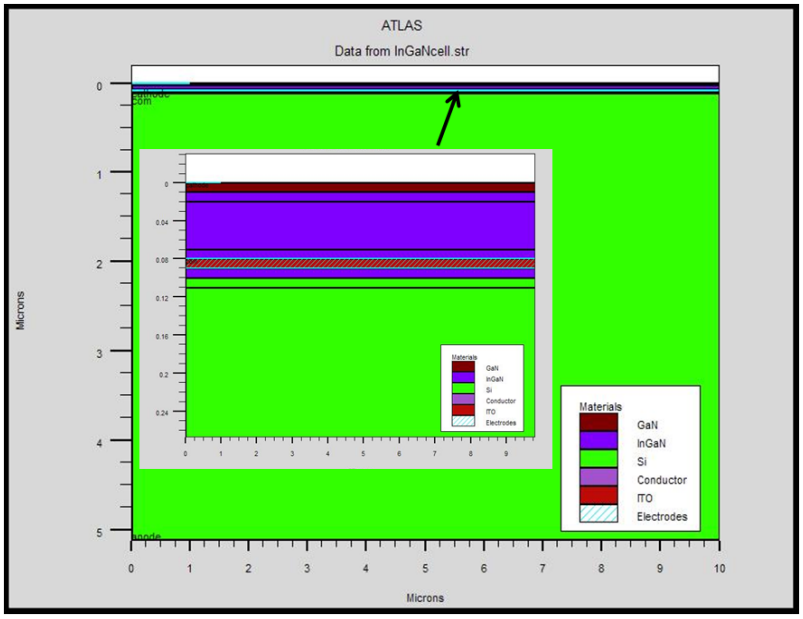


Fig. 4: Structure of the InGaN/Si heterojunction tandem solar cell under the Silvaco-Atlas simulator.

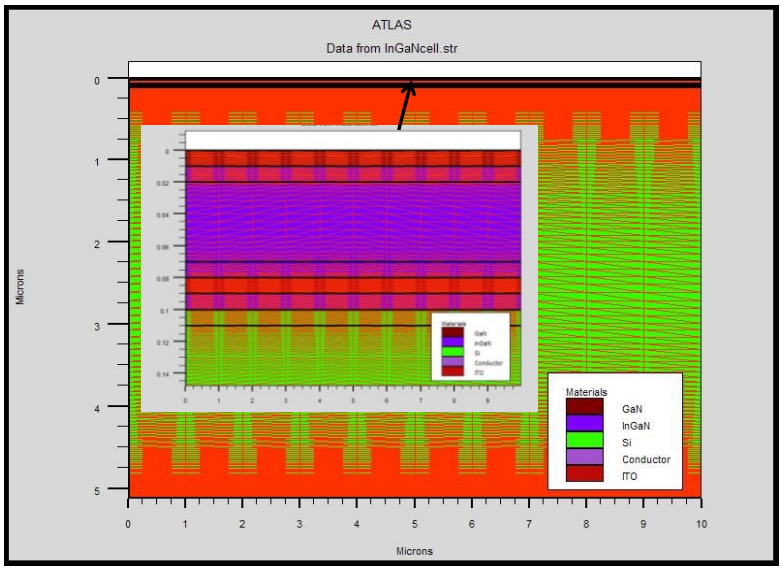


Fig. 5: Spacial mesh of the InGaN/Si heterojunction tandem solar cell under the Silvaco-Atlas simulator.

The simulation parameters associated with the studied InGaN/Si heterojunction tandem solar cell presented in Table 1 taking into account the Silvaco-Atlas database. The mobilities of electrons (μ_n) and holes (μ_p) are calculated according to the models of mobility depending on the concentration of impurities [5], (the conmob command in

Silvaco-Atlas) and the mobility dependent on the lateral electric field (the fldmob command in Silvaco-Atlas)[6-7].We suppose thermal equilibrium as boundary conditions, which means that the surface recombination velocities of electrons and holes(S_n and S_p) are taken to be equal to at the upper interface of the cell (Cathode/GaN) and the lower one (Anode/Si).
The optical parameters (refractive index and extinction coefficient) of the different layers constituting the studied cell are used from Silvaco database, and they are presented in Figs. 6-8.

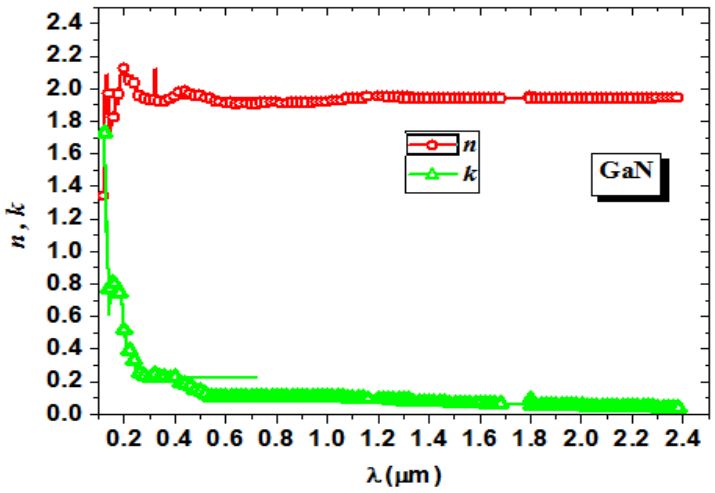


Fig. 6: Optical parameters (n and k) of the GaN used as the optical window according to the Silvaco database

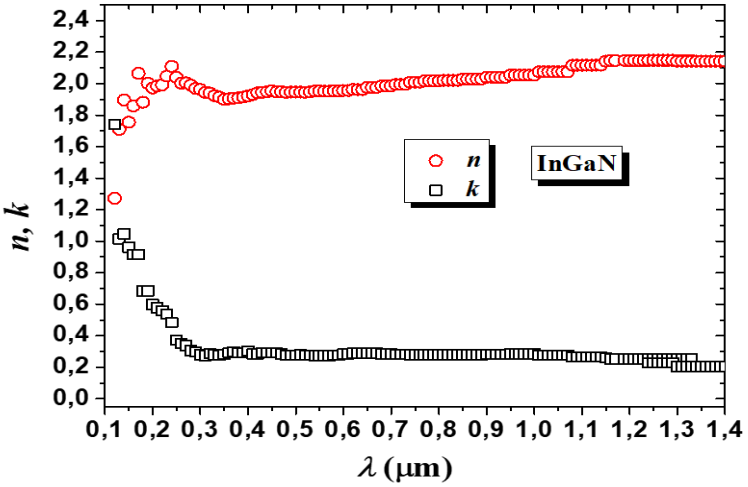


Fig. 7: In0.57Ga0.43N optical parameters (n and k) from the Silvaco database

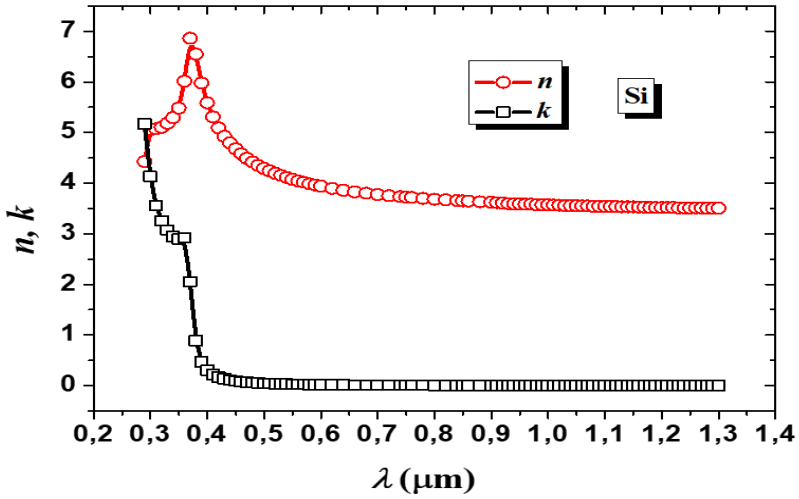


Fig. 8: Optical parameters of Si based on Silvaco's database.

3 Results and discussion:

Fig. 9 shows the energy band gap profile of the InGaN/Si heterojunction tandem solar cell, at thermal equilibrium. The alignment of the quasi-Fermi levels (E_{fn} and E_{fp}) is well satisfied through the different regions of the cell.

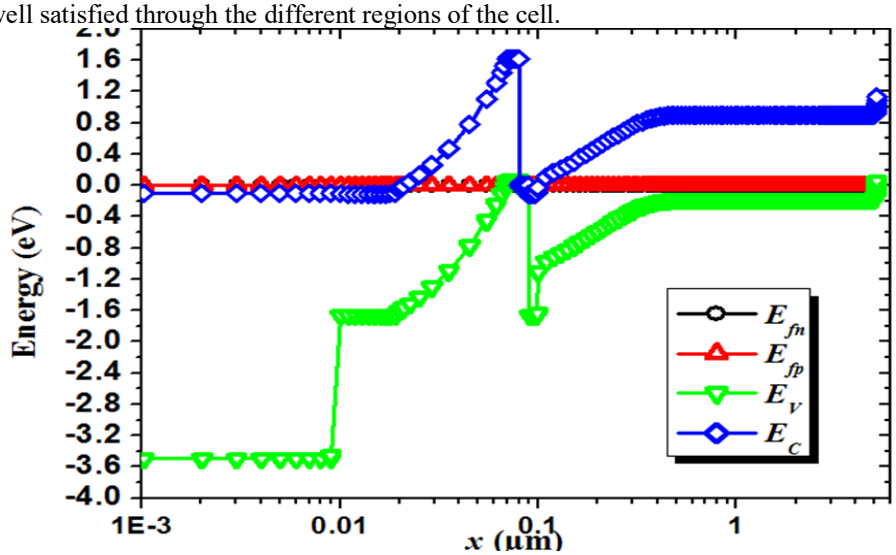


Fig. 9: Energy band gap profile of the InGaN/Si heterojunction tandem solar cell at thermal equilibrium.

As shown in figs. 10 and 11 respectively, theAM1.5 illumination leads to a splitting of quasi-Fermi levels. The splitting is more important by going from the short circuit to the open circuit conditions. The illumination has an effect to reduce the barrier potential height. The reduction happens firstly at the top sub-cell level as shown by the short circuit condition (fig. 10), then touches the bottom sub-cell in open circuit condition (fig. 11).

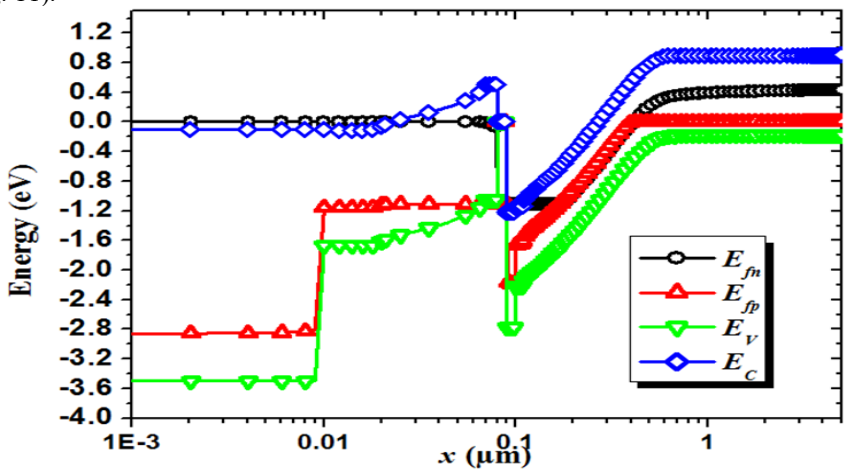


Fig. 10: Energy band gap profile of the InGaN/Si heterojunction tandem solar cell at short circuit condition.

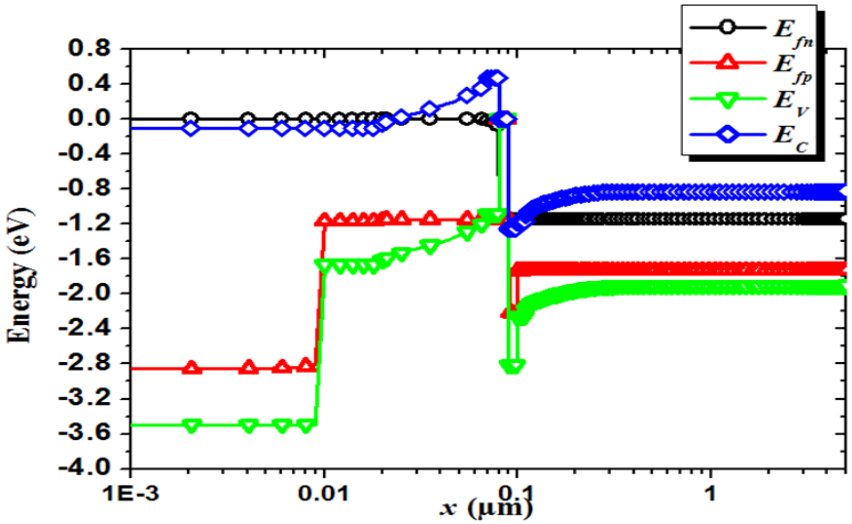


Fig. 11: Energy band gap profile of the InGaN/Si heterojunction tandem solar cell at open circuit condition.

Fig. 12 shows the free carrier density (n and p) profile of the InGaN/Si heterojunction tandem solar cell. The densities know a significant increase from thermal equilibrium to the short circuit condition mainly at the top sub-cell level. The considerable increment of them in the bottom sub-cell happens at the open circuit condition.

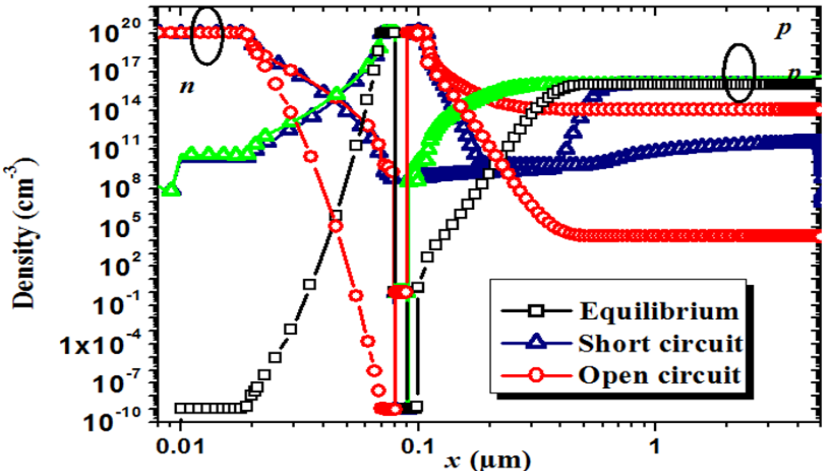


Fig. 12: Free carrier density (n and p) profile of the InGaN/Si heterojunction tandem solar cell, at thermal equilibrium, short circuit and open circuit conditions respectively.

The sensitivity to illumination of the electric field and potential can be notified from figs .13 and 14 respectively. The reduction in the field magnitude and the barrier potential height touches firstly the top sub-cell at short circuit condition, then the bottom sub-cell in open circuit condition

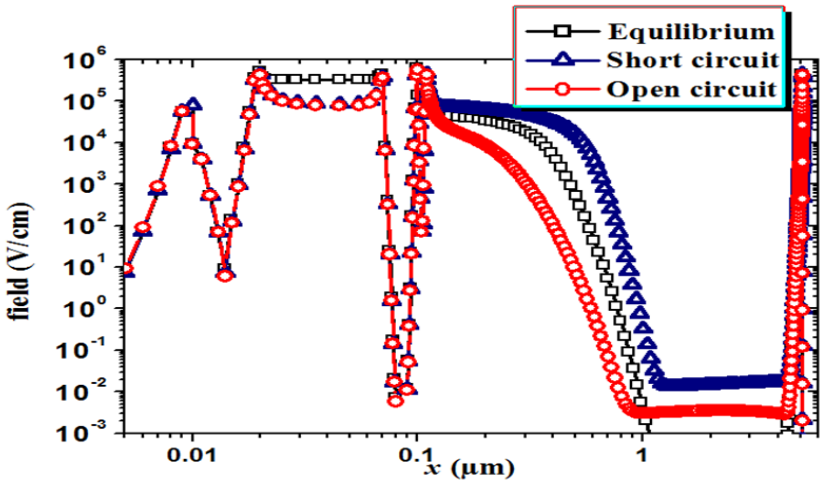


Fig. 13: Electric field profile of the InGaN/Si heterojunction tandem solar cell, at thermal equilibrium, short circuit and open circuit conditions respectively.

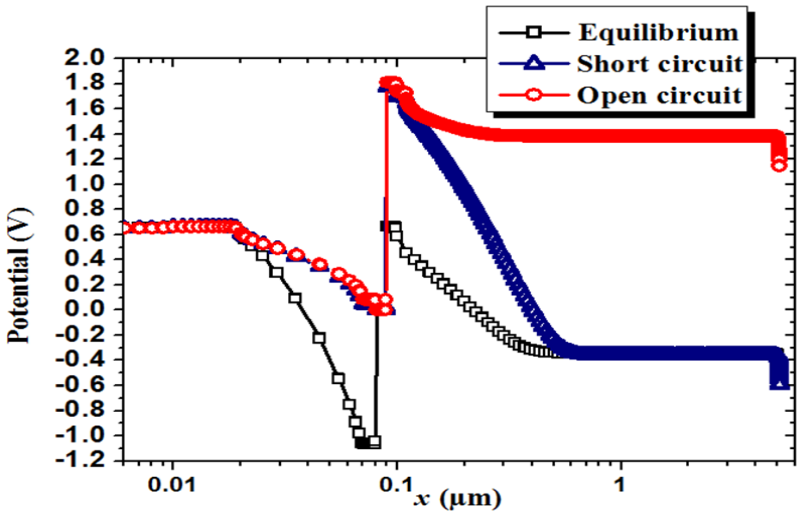


Fig .14: Electric potential profile of the InGaN/Si heterojunction tandem solar cell, at thermal equilibrium, short circuit and open circuit conditions respectively.

Figs .15 and 16 present, respectively, the current density - voltage (J-V) and the power - voltage (P-V) electrical characteristics of the InGaN/Si heterojunction tandem solar cell under AM1.5 illumination. The photovoltaic parameters of the cell, extracted from J-V characteristic (see table 1) show a satisfied value of 20.72% for the conversion efficiency.

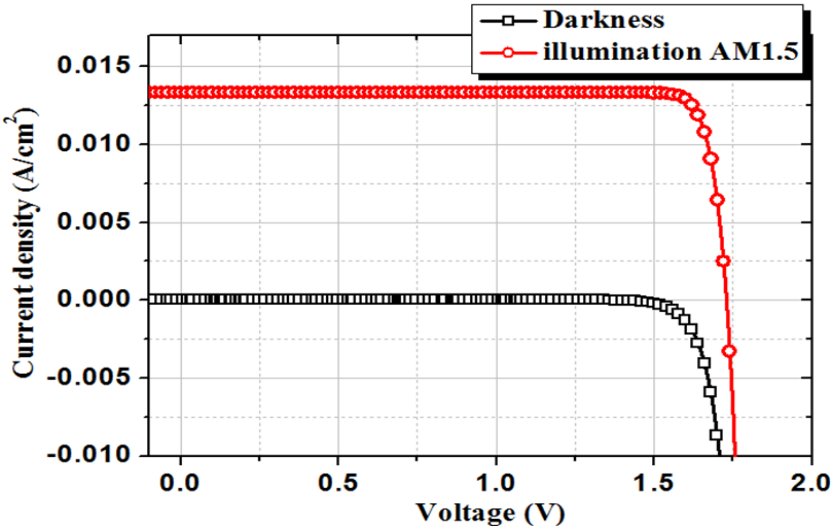


Fig .15: Current density - voltage (J-V) electrical characteristics of the InGaN/Si heterojunction tandem solar cell, in the dark and under AM1.5 illumination, respectively.

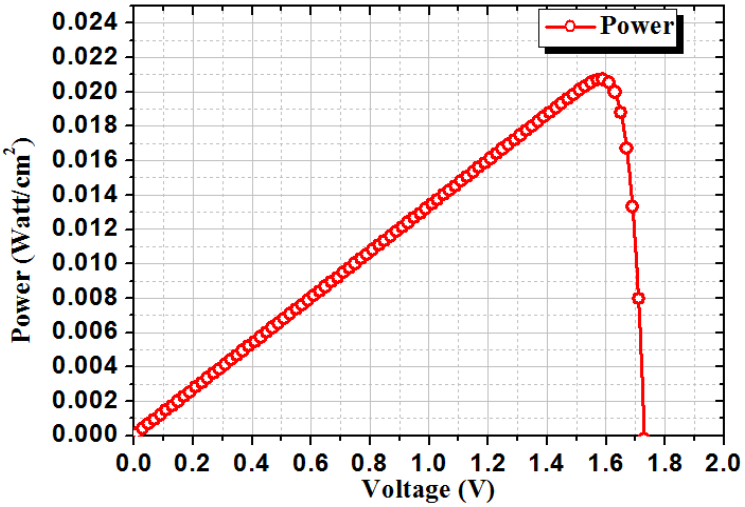


Fig .16: Power - voltage (P-V) electrical characteristic of the InGaN/Si heterojunction tandem solar cell under AM1.5 illumination.

Table 1: Photovoltaic parameters of the InGaN/Si tandem solar cell from J-V characteristic under AM1.5 illumination.

	J_{sc} (mA/cm^2)	V_{oc} (V)	P_{max} (W/cm^2)	*FF* (%)	η (%)
InGaN/Si tandem solar cell	13.34	1.72954	0.0207238	89.822	20.7238

Figu .17 shows the J-V characteristics of the InGaN/Si tandem solar cell under AM1.5 illumination for different thicknesses of the p-type base layer of the bottom sub-cell. The other layer thicknesses are fixed as defined in section .2. Fig .18 shows the P-V characteristics of the cell under the same conditions. The corresponding photovoltaic parameters are presented in table 3 and figs 19 and 20 respectively.

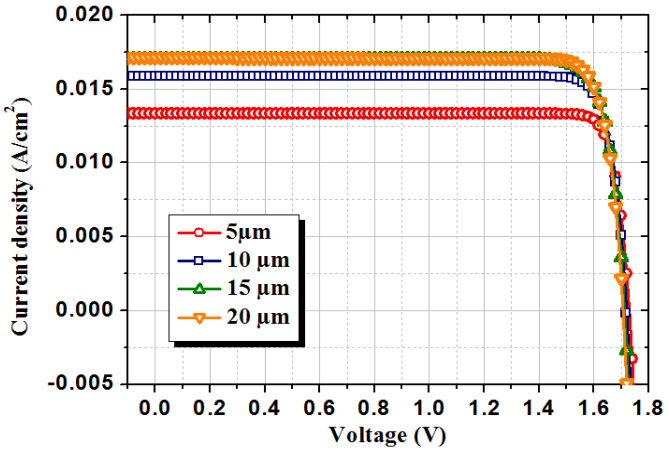


Fig .17: Current density - voltage (J-V) characteristics of the InGaN/Si tandem solar cell under AM1.5 illumination for different thicknesses of the p-type base layer of the bottom sub-cell.

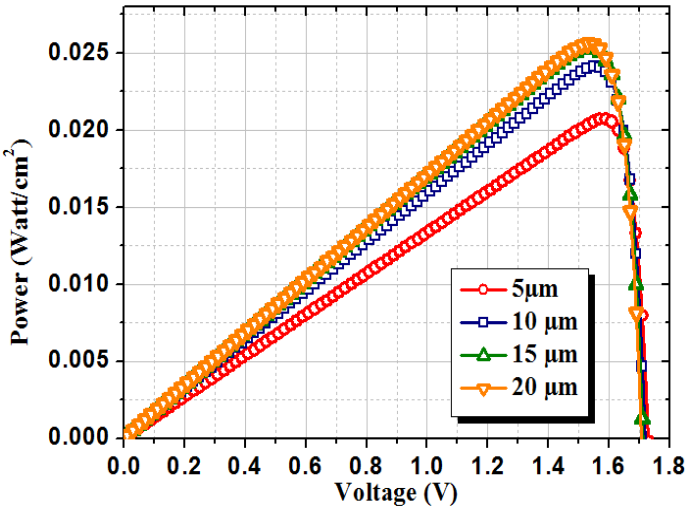


Fig .18: Power - voltage (P-V) characteristics of the InGaN/Si tandem solar cell under AM1.5 illumination for different thicknesses of the p-type base layer of the bottom sub-cell.

Table .2: Photovoltaic parameters of the InGaN/Si tandem solar cell, extracted from J-V characteristics under AM1.5 illumination for different thicknesses of the p-type base layer of the bottom sub-cell

	J_{sc} (mA/cm^2)	V_{oc} (V)	P_{max} (W/cm^2)	*FF* (%)	η (%)
5 µm	13.34	1.72954	0.0207238	89.822	20.7238
10 µm	15.83	1.71933	0.0240936	88.5241	24.0936
15 µm	17.04	1.71208	0.0253052	86.7393	25.3052
20 µm	17.13	1.70671	0.0255994	87.5614	25.5994

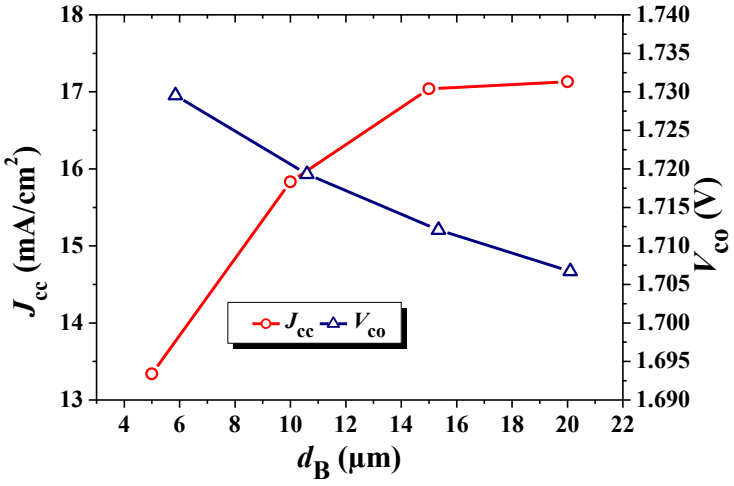


Fig .19: J_{SC} and V_{OC} behaviour of the InGaN/Si tandem solar cell for different thicknesses (d_B) of the p-type base layer of the bottom sub-cell.

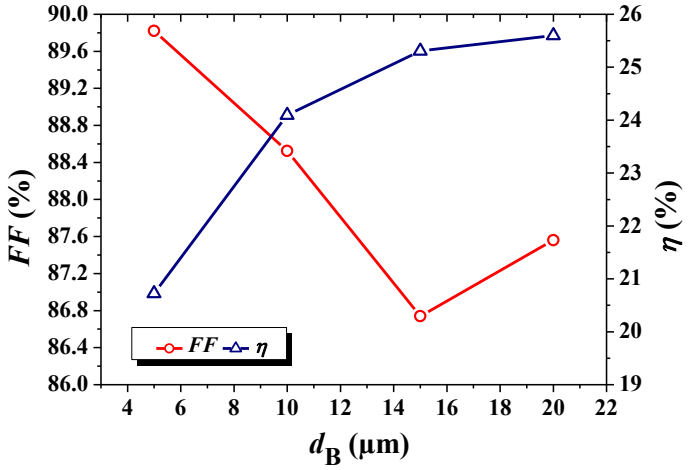


Fig .20: FF and η behaviour of the InGaN/Si tandem solar cell for different thicknesses (d_B) of the p-type base layer of the bottom sub-cell.

The thickness increase of the bottom sub-cell base layer, from 5µm to 20µm, brings an improvement to J_{SC} and P_{max} which leads to an amelioration of the conversion efficiency η from20.72 % to 25.59 %.

Fig .21 shows a comparison between three cases of the solar cell: based-Si single solar cell - InGaN/Si single solar cell [8] and InGaN/Si tandem solar cell, respectively, for the conversion efficiency η dependency on the base layer thickness d_B. We can see a significant improvement of η achieved by the tandem configuration relatively to the single solar cell.

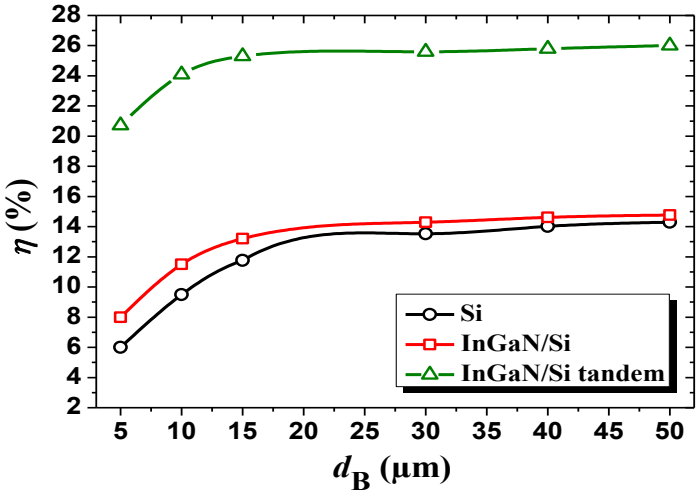


Fig .21: Conversion efficiency η dependency on base layer thickness d_B for the three cases: based-Si single solar cell - InGaN/Si single solar cell [8] and InGaN/Si tandem solar cell, respectively.

4 Conclusion

InGaN based semi-conductors' materials have the potential to make a major breakthrough in the photovoltaic industry. In fact, these materials have unique characteristics for producing solar cells with a very high conversion efficiency and at low cost: very high absorption coefficient throughout the spectrum of the solar spectrum, high mobilities, relatively low effective masses, a gap electronic scanning the entire visible spectrum, from near Infrared to ultraviolet, very high resistance to radiation and other extreme conditions. Recent work has shown that the InGaN alloy is also studied for the formation of tandem heterojunction

We presented a detailed description of our study carried on a tandem solar cell, based on Indium Gallium Nitride (InGaN)/ Silicon (Si) heterojunction. The top sub-cell material is chosen to be In0.57Ga0.43N, which has a calculated band gap of $E_g \cong 1.559$ eV corresponding to the maximum energy of the solar spectre AM1.5. The bottom sub-cell material is crystalline silicon with lower band gap of $E_g \cong 1.08$ eV. The solar cell was investigated under the standard global solar spectrum (AM1.5G) illumination with ~ 0.1 Watt/cm2 total incident power density, and 300°K ambient temperature. The study is mainly by numerical simulation using, as a tool, the SILVACO-ATLAS software. This latter allowed us to calculate the device performance parameters such as the current density-voltage and the power-voltage characteristics, (J-V) and (P-V) respectively, the short-circuit current density (J_{sc}), the open-circuit voltage (V_{oc}), the maximum power (P_{max}) delivered by the cell, the fill factor (FF), and the conversion efficiency (η).

The photovoltaic parameters of the investigated solar cell show a satisfied value of 20.72% for the conversion efficiency. Furthermore, the thickness increase, from 5µm to 20µm, of the bottom sub-cell base layer brings an improvement to J_{SC} and P_{max} which leads to an amelioration of the conversion efficiency η from 20.72 % to 25.59 %. The improvement of η achieved by the tandem cell configuration is significant relatively to the single solar cell based on Si or on heterojunction InGaN/Si.

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