SIMULATION OF ELECTRICAL PARAMETERS AND THICKNESS OPTIMIZATION OF AlSb/GaSb TANDEM SOLAR CELL

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Abstract
This paper presents a simulation work based on a four-terminal and mechanically stacked double junction tandem solar cell consisting of Aluminium Antimonide (n-AlSb/p-AlSb) top p-n junction and Gallium Antimonide (n-GaSb/p-GaSb) bottom p-n junction. This is based on the appropriate band gaps of the materials which make them suitable for solar spectrum absorption. The work is aimed at enhancing the solar spectrum absorption of the n-GaSb/p-GaSb single junction solar cell by using it as a bottom junction in the tandem cell, using simulation method. This was achieved by the absorption of the solar spectrum in the respective junctions of the proposed tandem cell using the junctions' cut-off wavelengths. The cell characterization was carried out using computer simulation software SCAPS and optimum performance of the cell was obtained. The work also, determined the optimum thickness of the individual junctions corresponding to the highest efficiency of the sub- cell. The n-AlSb/p-AlSb top junction was simulated with 1000Wm^{-2} incident power and obtained highest efficiency of 15.22% at an optimum thickness of 0.4µm. The n-GaSb/p-GaSb junction was simulated as a single junction solar cell with1000Wm^{-2}, and obtained highest efficiency of 16.34% at an optimum thickness of 3x10^{3}µm. However, when simulated with 399.99Wm^{-2} as a bottom junction of the tandem solar cell, n-GaSb/p-GaSb junction produced highest efficiency of 22.90% at an optimum thickness of 3x10^{3}µm. Therefore, the performance of n-GaSb/p-GaSb single junction is better when used as a bottom junction, in the AlSb/GaSb tandem solar cell, since its efficiency is higher than when it is used as a single junction solar cell. The result obtained for the four-terminal tandem cell shows an optimum electrical conversion efficiency of 38.12%. This result is in agreement with the theoretical value predicted in literature using a combination of similar bandgaps.

Keywords: photovoltaics, thickness optimization, tandem solar cells, AlSb, GaSb, SCAPS, Cut-off wavelength

Introduction

The world's fossil fuel resources may not sustain current energy requirements beyond the next few decades and therefore, the need for inexpensive alternative energy resources (Rashmi, 2012). However, environmental issues like global warming and the rising cost of producing electricity from fossil fuels have resulted in shifting focus towards renewable resources (Antonio & Steven, 2003). Renewable energy from sources such as the sun, wind, rain and tides is safe and more reliable. The renewable energy resources are in abundance and by far the safest sources of energy available on earth (Rashmi, 2012). The device that uses solar energy to generate electricity by the photovoltaic effect is known as a Photovoltaic cell or Solar Cell.

The advent of new technologies has made it possible to overcome the surface recombination that had been the cause of limitation in efficiency of solar cells. These technologies used window layer to produce cells with efficiencies in the range of 17-19% from 1970-1993 and up to 28% in 2005 for other GaAs solar cells structures (Wikipedia, 2020). But as early as 1961 Shockley and Queisser, in their work have predicted theoretical efficiency limit of 30% for a single p-n junction solar cell illuminated by AM1.5 solar spectrum. The report also stated that photons with energy exceeding the band gap energy of the semiconductor loose the excess energy by thermalisation, which is the conversion of the excess energy to heat (Shockley & Queisser, 1961).

One of the most developed ways of enhancing the photon energy absorption of the solar cells is the use of multi-junction (MJ) solar cells (King; 2018; Merteins, 2015). This solar cell, typically, has two or more p–n junctions made from different materials having different bang gap energy. The different junctions can be stacked on top of one another, with metallic contacts on the top and bottom materials of the solar cell. A stacked tandem device of this kind was first introduced in the late 1970s; and consists of two subcells with each having a p–n junction: The bottom cell was based on gallium arsenide (GaAs) and the top cell (exposed to sunlight) was based on aluminium gallium arsenide. A different approach was later developed by the National Renewable Energy Laboratory (NREL) based on indium gallium phosphide (or InGaP alloy) junction on top of GaAs middle junction grown on a germanium (Ge) substrate. The GaInP, GaAs, and Ge of the triple-junction cell developed at NREL were selected because they have a desirable complement of bandgap energies and because they have a matching lattice constant (Brenton, 2002). Subsequent developments resulted in the replacement of the GaAs with InGaAs alloys. This stacked-subcells approach has resulted in MJ solar cells of conversion efficiency above 40% (Eduardo e*t al.,* 2015). The idea is to absorb the various incident solar spectrums by the different junctions in order to improve the solar conversion efficiency of the entire tandem solar cell. This optimizes the light absorption and photocurrent generation of each junction of the sub-cells down to the narrow wavelength range (Eduardo, *et al*, 2015).

This work, therefore, proposes a tandem solar cell of Aluminium Antimonide (AlSb) homojunction on top of GaSb homojunction. This was aimed at absorbing as much of the solar spectrum including high energy photons and at same time reduces the thermalization effect of the single junction of GaSb. The selection of AlSb (E_g =1.63eV) and GaSb (E_g = 0.72eV) materials was based on their suitable energy bandgaps. Their energy bandgaps are close to a combination of two band gaps, 1.73 and 0.94eV used in a theoretical work on bandgap combinations, independent of materials, in which a 2-junction four terminals solar cell was formed. The four terminals solar cell formed produced an efficiency of 46.1% under standard test condition (Filipič *et al,* 2015).

Theoretical Background

This work proposes a four-terminal tandem configuration. The structure comprises of two p-n homojunction of AlSb (n-AlSb/p-AlSb) and GaSb (n-GaSb/p-GaSb) having band gap energy 1.63eV and 0.72eV respectively. These were stacked together with AlSb as the top cell while the GaSb as the bottom cell. The top and bottom sub-cells of the four-terminal structure are optically coupled by a thick non-absorbing layer.

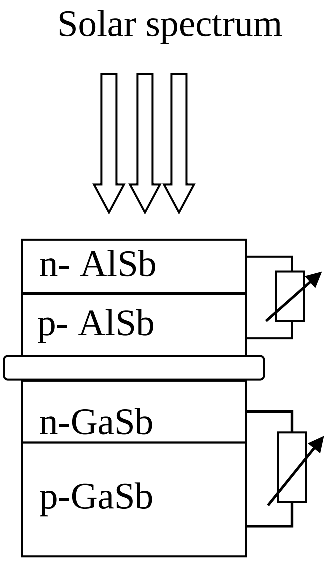

Figure 1: Four-Terminal AlSb/GaSb Tandem Solar Cell Structure

The transmission of light is through the top sub-cell down to the bottom sub-cell. This implies that the light absorption at the bottom junction depends on the absorption and transmission properties of the top junction, Figure 1.
The spectral distribution and short circuit current generation in the two junctions are expressed as (White *et al*. 2013):

$$J_{sc}^{(1)} = q\int_0^{\infty} \phi_{A.M1.5G}(\lambda) QE(\lambda)^{(1)} d\lambda \quad (1)$$

$$J_{sc}^{(2)} = q\int_0^{\infty} \phi_{A.M1.5G}(\lambda) T^{(1)} QE(\lambda)^{(2)} d\lambda \quad (2)$$

where $J_{sc}^{(1)}$ and $J_{sc}^{(2)}$ are the short-circuit currents of top and bottom sub-cells, $\phi_{AM1.5G}(\lambda)$ is the incident photon flux, q is the electron charge, $\phi_{AM1.5G}(\lambda) T^{(1)} (\lambda)$ is the photon flux transmitted through the top junction, $QE(\lambda)^{(1)}$ and $QE(\lambda)^{(2)}$ are the quantum efficiencies of the two junctions respectively.

The quantum efficiency QE (λ) measures the ratio of the amount of electron-hole pairs created to the incident photons at a given wavelength, λ and is given by:

$$QE_i(\lambda) = \frac{J_{sci}(\lambda)}{\phi_i(\lambda)} \quad (3)$$

where $\varphi_i(\lambda)$ is the photon flux of the incident light in subcells i.
The value of QE (λ) is obtained by linking it with the absorption coefficient α(λ). Assuming each photon absorbed by a cell creates an electron/hole pair. This leads to;

$$QE(\lambda)^{(i)} = 1 - \exp(-\alpha W) \quad (4)$$

where the superscript (i) refers to the top cell and W is the cells thickness and exp(-αW) is the incident light which is not absorbed by the sub cell *i* (transmitted light, T).
From equation (4), the light transmitted through the top $T^{(i)}$ cell to the bottom cell is given by

$$T^{(i)} = 1 - QE(\lambda)^{(i)} \quad (5)$$

Assuming only Photons with energy below the band gap of the AlSb top junction cell are transmitted to the GaSb bottom cell where a large fraction is absorbed. To make this possible, the top cell is also assumed to be infinitely thick. In this case, using equation (4) the transmitted photons through the top junction can be expressed as:

$$T^1 = \exp(-\alpha W) = 0 \quad (6)$$

ie $QE(\lambda)^{(i)} = 1$

For all photons whose energy E_{gt}, is higher than that of the AlSb material of the top junction, and $T^{(1)}(\lambda) = 1$ equations (1) and (2) can be approximated to

$$J_{sc}^{(1)} = q\int_{0}^{\lambda_t} \phi_{A.M1.5G}(\lambda)d\lambda \qquad (7)$$

$$J_{sc}^{(2)} = q\int_{\lambda_t}^{\lambda_b} \phi_{A.M1.5G}(\lambda)d\lambda \qquad (8)$$

Where $\lambda_b = hc/E_{gb}$ and $\lambda_t = hc/E_{gt}$ are called critical or cutoff wavelengths which correspond to the band gaps of the bottom and top cells respectively. If the wavelength of the radiation exceeds this value, then the energy of the photon is less than E_g and such a photon cannot cause a valence band electron to enter the conduction band (Millmam and Halkias, 2005; and Singh and Ravindra 2012) expressed this wavelength as;

$$\lambda_g = \frac{1240}{E_g(eV)}(nm) \qquad (9)$$

In this work, using equation (9) the value of cutoff wavelength for AlSb with band gap of 1.63eV, λ_t= 760nm and similarly for GaSb (0.72eV), λ_b=1722nm. These values of cutoff wave lengths for top and bottom junctions were used in the SCAPS action panel's spectrum cutoff settings during simulation of the GaSb bottom junction in order to filter the photons which are within the absorption range of the top AlSb junction from reaching the bottom GaSb junction. Therefore, equations (7) and (8) become

$$J_{sc}^{(2)} = q\int_{0}^{760nm} \phi_{A.M1.5G}(\lambda)d\lambda \qquad (10)$$

$$J_{sc}^{(2)} = q\int_{760nm}^{1722nm} \phi_{A.M1.5G}(\lambda)d\lambda \qquad (11)$$

The Photons within this cut-off wavelengths interval of the solar spectrum of Power (1000W/m^2) are assumed to be absorbed by the bottom junction.

Absorption coefficient α (**λ**) is the number of photons absorbed per unit length of the material which is given by the analytical approximation;

$$\alpha(\boldsymbol{\lambda}) = \boldsymbol{\alpha_o}\left(\frac{\boldsymbol{E_\phi(\lambda) - E_g}}{\boldsymbol{kT}}\right)^{\boldsymbol{1/2}} \qquad (12)$$

where a_0 is the characteristic absorption coefficient for the material, $E\phi(\lambda) = hc/\lambda$ is the incident photon energy at wavelength λ, E_g is band gap energy of a semiconductor, k is the Boltzmann constant, and T is the cell temperature.

The efficiency of the four terminal tandem solar cell whose junctions are optically coupled is determined by the sum of the efficiency of the individual sub-cells making the tandem solar cell (Filipič et al, 2015, Reynolds and Smirnov, 2015, and Musk, 2016), therefore,

$$\eta_{\text{tandem}} = \eta_{\text{AlSb}} + \eta_{\text{GaSb}} \qquad (13)$$

Simulation Method

This section presents the simulation procedure of AlSb-GaSb four- terminal tandem solar cell which was conducted using SCAPS version 3.3.0.6. The simulation was carried out under standard test condition of solar incident power corresponding to air mass AM1.5 (1000W/m^2), and ambient temperature of 300°K. The parameters of the AlSb and GaSb materials used in the problem definition panel of the SCAPS software are contained in table 1 (Adachi, 2005; Bouzid & Dehimi, 2012; Dhakal *et al,* 2011).

Table 1: Properties of AlSb and GaSb materials used in SCAPS simulation software

Parameter	AlSb	GaSb
Band Gap (eV)	1.63	0.72
Dielectric constant at 300K	11.21	15.7
Electron mobility μ_n at 300K (cm^2/Vs)	200	5650
Hole mobility μ_h at 300K (cm^2/Vs)	420	875
Density of electrons in the conduction band, N_c (cm^{-3})	7.80×10^{17}	2.078×10^{17}
Density of holes in the valence band, N_v (cm^{-3})	1.80×10^{19}	1.770×10^{19}
Acceptor or donor density, N_A or N_D (cm^{-3})	$N_{A=}\ 1\times 10^{14}$ $N_{D\ =\ 10}{}^{5}$	$N_{A\ =}\ 5x10^{19}$ $N_{D\ =}$ $2x10^{18}$
Capture cross section of electrons (σ_e)(cm^2)	1.00×10^{-8}	8×10^{-19}
capture cross section of holes (σ_p)(cm^2)	1.00×10^{-11}	9×10^{-15}
electron effective mass, m^*_n/m_o	0.14	0.047
hole effective mass, m^*_p/m_o	0.21	0.5
Electron affinity χ_e (eV)	3.65	4.5
Electron thermal velocity ($\upsilon_{th,}$ cm/s)	10^7	$5x10^7$
Hole thermal velocity ($\upsilon_{th,}$ cm/s)	10^7	$2X10^7$
Absorption constant (m^{-1})	10^5	10^5

Simulation of the proposed AlSb/GaSb four-terminal tandem cell

To simulate the four-terminal AlSb/GaSb tandem cell, the top and bottom junctions were simulated separately. This was done in order to examine the spectrum bands absorbed by the respective junctions of the tandem cell. The performances of these junctions were then added up to give the total response of the tandem cell in accordance with equation (13). Using equations (11) and (12), the incident power on n-GaSb/p-GaSb bottom junction was 399.99W/m^2 as calculated by the SCAPS software. These equations imply that the n-AlSb/p-AlSb top junction absorption is assumed to be in the ultraviolet and visible range of solar spectrum while the n-GaSb/p-GaSb takes over from there up to 1722nm in the near infrared region. In this respect, the bottom cell receives the filtered photon flux, as described by equation (12). The simulation flow chart for both top and bottom junction is the same and is shown in Figure, 2. The only difference is in the third step after 'Run SCAPS' where the cutoff wavelength corresponding to 399.99Wm^{-2} incident power should be selected in the case of the bottom junction.

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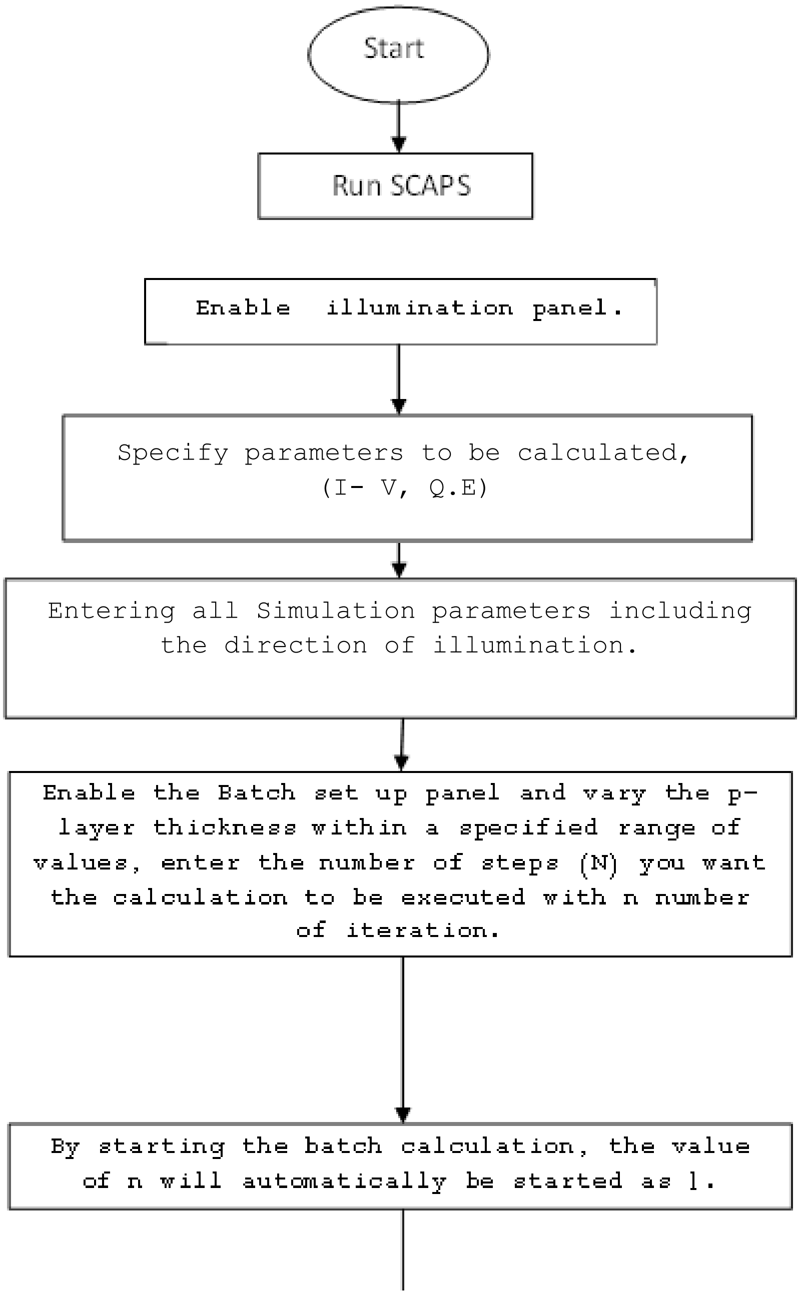
Start
Run SCAPS
Enable illumination panel.
Specify parameters to be calculated, (I- V, Q.E)
Entering all Simulation parameters including the direction of illumination.
Enable the Batch set up panel and vary the p-layer thickness within a specified range of values, enter the number of steps (N) you want the calculation to be executed with n number of iteration.
By starting the batch calculation, the value of n will automatically be started as 1.

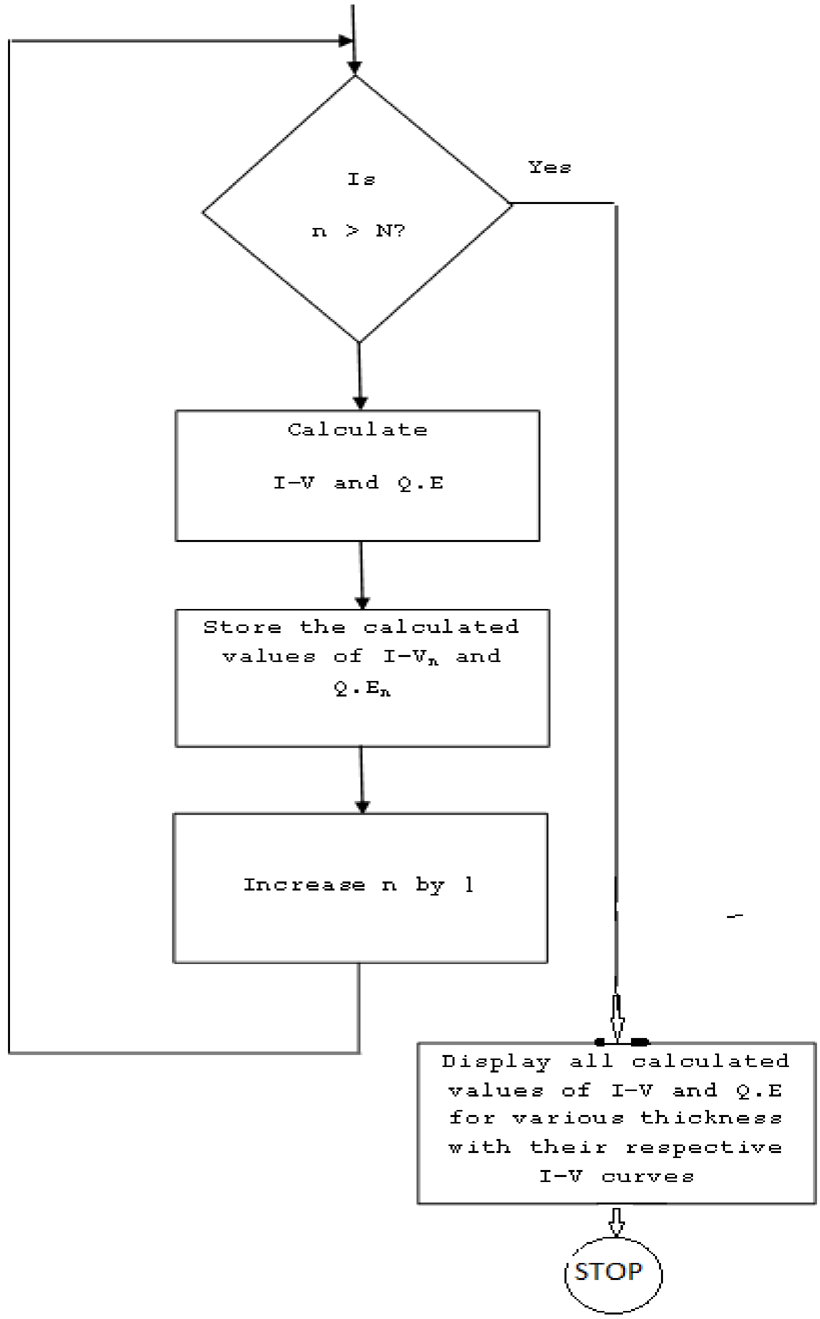

Figure 2: Simulation Flow Chart of the Top and Bottom single Junctions

Firstly, using the incident solar photon flux of 1000W/m^2, the top single junction of n-AlSb/p-AlSb was simulated. The operation of the junction under various thicknesses was evaluated. The efficiency of this single junction as a function of thickness was subsequently determined.

Secondly, the simulation study of the n-GaSb/ p-GaSb was carried out using two separate solar flux values. This was as a result of the n-GaSb/ p-GaSb being used in this case as a bottom junction. The amount of the incident flux reaching the bottom junction was calculated to be 399.99W/m^2. Therefore, the single junction of n-GaSb/ p-GaSb was simulated using 1000W/m^2 and 399.99W/m^2 respectively, and the efficiency as a function of thickness for both cases also determined for the sub-cell.

Finally, the efficiency of the four-terminal tandem solar cell was determined. This was done by summing up the efficiencies of the top and the bottom sub-cells using equation (13).

Results and Discussion

The simulation results of the single n-AlSb/ p-AlSb top junction and that of the single n-GaSb/ p-GaSb bottom junction are presented and discussed. The overall performance was obtained by summing up the performance of these top and bottom junctions.

Results of the single n-AlSb/ p-AlSb top junction.

The variation of the top AlSb junction base layer thickness in the range 0.1 to 30μm was obtained, Figure 3. The results obtained are V_{oc} = 1.51V, J_{sc} = 21.28mA/cm^2, FF = 47.32% and η = 15.22% at the optimum base layer thickness of 0.4μm. These represent the optimum values for the junction.

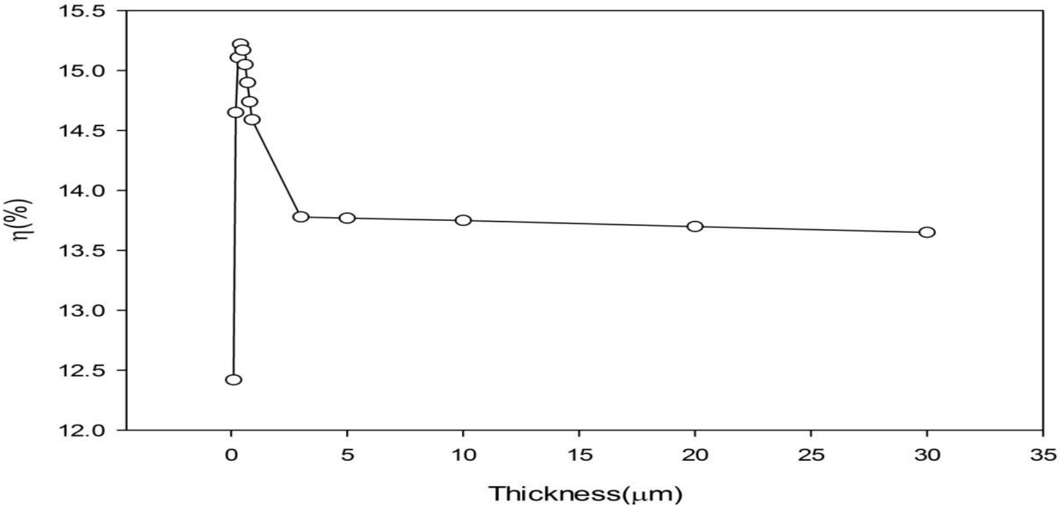

Figure 3: Graph of Efficiency Variation against Thickness for n-AlSb/ p-AlSb Top Junction

Results of the single n-GaSb/ p-GaSb bottom junction

The results presented in this section were obtained for the performance of n-GaSb/ p-GaSb base junction under two different illumination conditions. The conditions are the normal 1000Wm^{-2} and that of the radiation reaching the junction 399.99Wm^{-2}, when used in the tandem cell.

Firstly, the results of the n-GaSb/ p-GaSb single junction base layer thickness variation in the range 0.1 to 1x10^4 μm using 1000 Wm^{-2} were obtained. This was done in order to study the effects of the variation of base layer thickness on the performance of the junction under normal illumination condition. The best results were obtained at the thickness of 3x10^{3}μm which include V_{oc}=0.38V, J_{sc}=56.30mA/cm^2, FF=76.11% and η=16.34%, Figure 4.

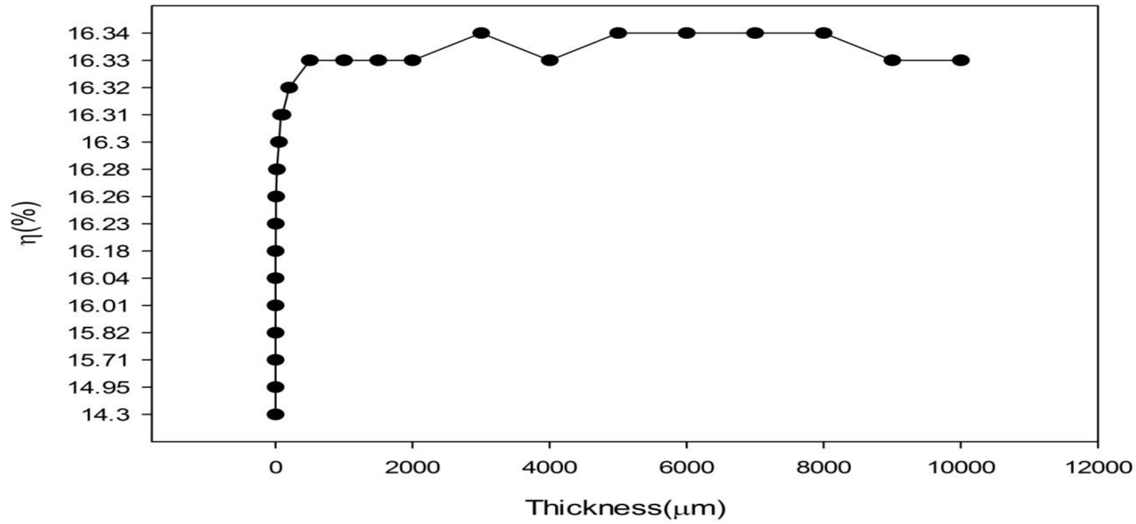

Figure 4: Graph of Efficiency against Thickness for n-GaSb/ p-GaSb Single Junction under 1000Wm^{-2}

The result did not show a V_{oc} drop over large thickness range and shows several raise and fall in $J_{sc,}$ as shown in figure 4.

Secondly, the results of the n-GaSb/ p-GaSb base layer thickness in the range 0.1 to 3x10^{3}μm using 399.9Wm^{-2} are presented. This was done in order to study the effects of the variation of base layer thickness on the performance of the junction under the amount of the radiation reaching it when used in the tandem cell. The best results were obtained at the thickness of 1.7 x10^{3}μm which include V_{oc}=0.37V, J_{sc} = 33.00mA/cm^2, FF = 75.61% and η = 22.90%, Figure 5.

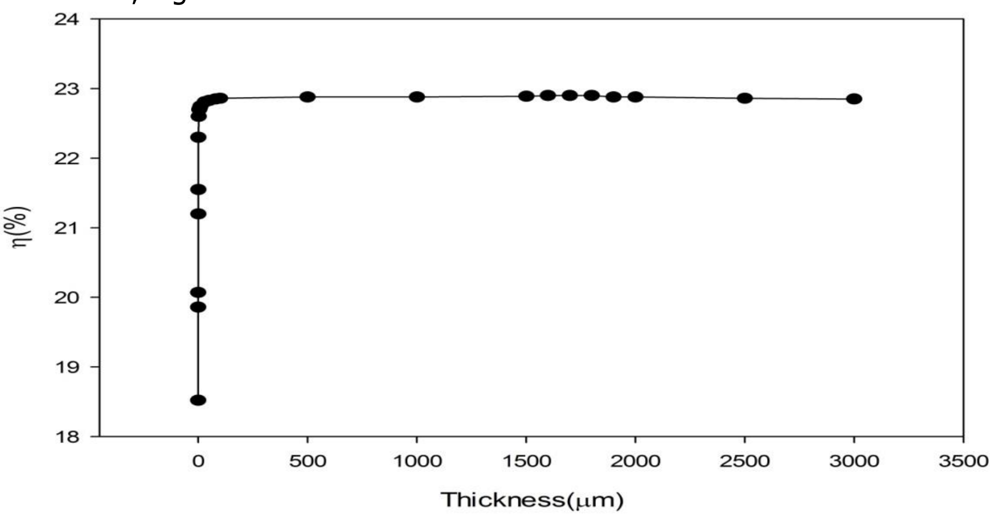

Figure 5: Graph Efficiency against Thickness for n-GaSb/ p-GaSb Bottom Junction under 399.9 Wm^{-2}

Generally, the effect of base layer thickness variation on the solar cell output parameters is that, power conversion efficiency increases as a result of increase in photocurrent due to enhanced flux absorption. When the efficiency reaches its maximum value, it then decreases as a result of decrease in V_{oc} due to increase in reverse saturated current (J_o).similarly, J_{sc} decreases when the cells thickness exceeds certain optimum value due to recombination phenomenon, since the free charge carriers generated much deeper into the bulk material have to travel longer distances before being collected. However, the thickness value that shows better conversion efficiency was selected as the optimum thickness.

Finally, the overall performance of the proposed tandem solar cell was obtained according to equation (13) that is using the results of both top n-AlSb / p-AlSb and n-GaSb / p-GaSb bottom pn- junctions forming the proposed four-terminal tandem solar cell. The efficiency obtained was 38.12%.

Conclusion

This work has successfully simulated and evaluated the performance of two junctions, four terminals tandem solar cell of n-AlSb/p-AlSb Top Junction and n-GaSb/p-GaSb Bottom Junction using SCAPS 1D software. The results obtained for the n-GaSb/p-GaSb Bottom Junction show that the junction efficiency of 22.90% under solar flux of 399.99Wm^{-2} is higher than the efficiency of 16.34% of the same junction under 1000Wm^{-2} solar flux. This shows that the n-GaSb/p-GaSb is more efficient when used in tandem solar cell than as a single junction solar cell. When used as a single junction solar cell there is thermalization effect as a result of photons of energy higher than the bandgap of the material. This is reflected in the low efficiency value of 16.34% under 1000Wm^{-2}. The efficiency of the tandem solar cell n-AlSb/p-AlSb and n-GaSb/p-GaSb was found to be 38.12%.

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