INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
A. Kowsar and S.F.U.Farhad, Vol.8, No.3, September, 2018

High Efficiency Four Junction III-V Bismide Concentrator Solar Cell: Design, Theory, and Simulation

Abu Kowsar‡ and Syed Farid Uddin Farhad

Solar Energy Conversion and Storage Research Section, Industrial Physics Division, BCSIR Laboratories, Dhaka, Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka-1205, Bangladesh.

(apukowsar@gmail.com, sf1878@my.bristol.ac.uk)

‡ Corresponding Author; Abu Kowsar, Industrial Physics Division, BCSIR Laboratories, Dhaka, Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhanmondi, Dhaka-1205, Tel: +88 017 228 1618, apukowsar@gmail.com

Received: 14.05.2018 Accepted:11.07.2018

Abstract- In this paper, the efficiency of a novel $GaInP_2/GaAs/GaAs_{0.94}Bi_{0.06}/Ge$ concentrator multijunction solar cell has been investigated by simulation using indigenously written code for MATLAB software. The materials in this unique cell structure are judiciously selected to ensure the maximum absorption of photons from ultraviolet to deep infrared wavelengths of the solar spectrum. A theoretical model has been developed to channel the same current in all four junctions as well as to ensure the highest conversion of the sunlight into electricity. The theoretical efficiencies of this quadruple junction solar cell have been simulated to be 49.6% and 60.2% for AM1.5G solar radiation under 1 sun and 500 sun concentration respectively. Finally, these simulated efficiencies have been compared with the theoretical and experimental efficiencies of the reported champion solar cells.

Keywords III-V bismide, multijunction solar cell, concentrator cell, efficiency, simulation

1. Introduction

Multijunction solar cells offer the champion solar cell efficiencies in photovoltaic literature. To surpass the single junction solar cell efficiency limitation and to achieve the very high efficiency, different research groups reported a list of cell configurations such as tandem cell, triple junction cell, four junction multijunction cells or even more. Incorporating the concentrator photovoltaic (CPV) technologies with multijunction solar cells promise further improvement of the overall cell efficiency (η). This CPV technologies significantly reduce the amount of material required for cell fabrication that consequently reduce the overall manufacturing cost of the multijunction solar cell. Concentrator multijunction solar cell is used for terrestrial application.

To realize ultrahigh efficiency solar cell, there have been growing interest in designing and developing quadruple junction solar cell among the photovoltaic community since the last decade of twenty century. In 1997, Sarah Kurtz *et al.*[1] designed a four layered GaInP/GaAs/(not specified)/Ge multijunction solar cell and projected an ideal theoretical efficiency of η >50%. In 1998, an GaInNAs active layer of 1eV bandgap(E_g) was used as third layer of four junction solar cell and reported a theoretical efficiency of 52% under 500 suns for AM1.5D [2]. Considering the optoelectronic properties of GaInNAs, an improved design of a four junction GaInP/GaAs/GaInNAs/Ge solar cell has been elucidated in 2002 [3]. Introducing new modeling techniques and using Silvaco ATLAS software package for capturing wide range of optoelectronics properties, another four junction solar cells was designed and published in 2005 [4]. With optimized chemical composition, GaInAs semiconductor materials of 1eV and 0.7eV bandgap have also been used in replacement of GaInNAs and Ge for third and bottom layer respectively of conventional four junction solar cell [5]. After that, different research groups reported a list of four junction solar cell configurations.

In recent years, a novel four layer configured $In_{0.51}Ga_{0.49}P/GaAs/In_{0.24}Ga_{0.76}As/In_{0.19}Ga_{0.81}Sb$ multijunction solar cell has been reported with theoretical efficiency 47.2% under 1 sun condition (normal atmospheric) [6]. At the same time, a new material, III-V bismide semiconductor of Eg = 1 eV has also been used as a third layer for four junction solar cell [7, 8]. For example, Sakib *et al.* [7] designed a novel four junction $GaInP_2/GaAs/GaAs_{0.94}Bi_{0.06}/Ge$ cell of 49.7% efficiency for AM1.5G for normal atmospheric condition, and Shamima *et al.* [8] further replaced the Ge bottom layer with 0.7eV bandgap $GaAs_{0.91}Bi_{0.0857}$ material and described another four junction cell $GaInP_2/GaAs/GaAs_{0.94}Bi_{0.0583}/GaAs_{0.91}Bi_{0.0857}$ of 52.2% efficiency for AM1.5G under 1 sun condition.

In this work, normal atmospheric condition is further extended to 500 sun concentrating condition of solar irradiance. We have proposed a novel $GaInP_2/GaAs/GaAs_{0.94}Bi_{0.06}$ (1eV)/Ge (0.67eV) for four junction concentrator solar cell and achieved theoretical efficiency ~49.6% and ~60.2% for AM1.5G solar radiation under 1 sun and 500 sun concentration respectively. The simulation results shows that with the incorporation of sun concentration factor leads to a linear increment in the short-circuit current and a ~10% increment in the overall solar cell efficiency.

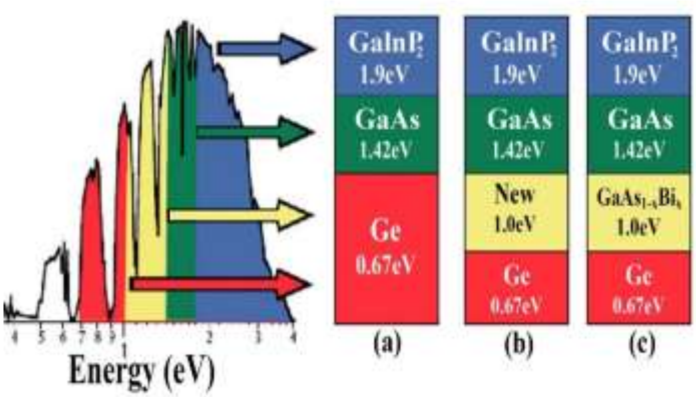

Fig.1. Different parts of solar spectrum absorbed by corresponding semiconductor materials are shown in (a)–(c). In (a), entire spectrum is absorbed by $GaInP_2/GaAs/Ge$ solar cell. In (b) an additional 1eV bandgap new material is introduced and in (c), a $GaAs_{1-x}b_x$ semiconductor of 1eV bandgap material is used for achieving novel four junction concentrator solar cell.

2. Proposed Four Junction Solar Cell

In this proposed multijunction solar cell, all sub-layers are comprised of III-V semiconductor materials with zinc blend crystal structure. The design used $GaInP_2$ of electronic bandgap 1.9 eV as top cell or first layer, GaAs of 1.42eV as middle cell or second layer and Ge of 0.67eV as bottom cell or fourth layer (*ca.* Figure 1 and 2). For third layer, Gallium Arsenic Bismide ($GaAs_{1-x}Bi_x$) has been proposed. To obtain this desired material, bismuth (Bi) content is mole fractionally mixed with GaAs. Although bismuth is considered as a non-radioactive toxic heavy metal but III-V bismide compound does not show any toxicity. However, it has been observed in literature that energy band-gap of GaAs is reduced by ~ 84 meV for each 1% percent of Bi content (x) [7-12]. The bandgap of GaAs is reduced by molecular beam epitaxy (MBE) and amount of Bi content is evaluated by Rutherford back scattering (RBS). So, for obtaining Eg = 1eV of GaAs0.94Bi0.0583 active layer, 5.83% of bismuth (Bi) content is incorporated with GaAs semiconductor material. As very small amount of Bi is mole fractionally mixed with GaAs, so the lattice constant of this desired active layer could be kept approximately the same [8, 11].

All four sub layers (top to bottom) are comprised of p-type and n-type layer creating four p-n junctions. Therefore, these four p-n junctions generate four different open circuit voltages. Every two adjacent sub layers are connected together by a tunnel junction. In practice, an extremely thin tunnel junction of wide bandgap [6] is produced in between every two successive layers from their corresponding layers (see Figure-2). As these layers are extremely thin in nature and originated from the corresponding sub layers (such as p-type $GaInP_2$ tunnel junction layer for first tunnel junction is originated from p-type $GaInP_2$ layer of top cell), so the thickness of tunnel junction layer along with its parent layer will be the same as original parent layer.

For attaining the maximum current and optical transparency channeling through top to bottom cells, it has been maintained that all these four sub-cells are lattice matched (lattice constant ~5.65Å) and series connected. An anti-reflecting coating layer has been used for minimizing the reflection loss and a wide bandgap AlInP material has been used as a window layer for ensuring maximum light entering the subsequent p-n junctions. The role of the front and back contacts is to collect the photo generated carriers from the solar cell.

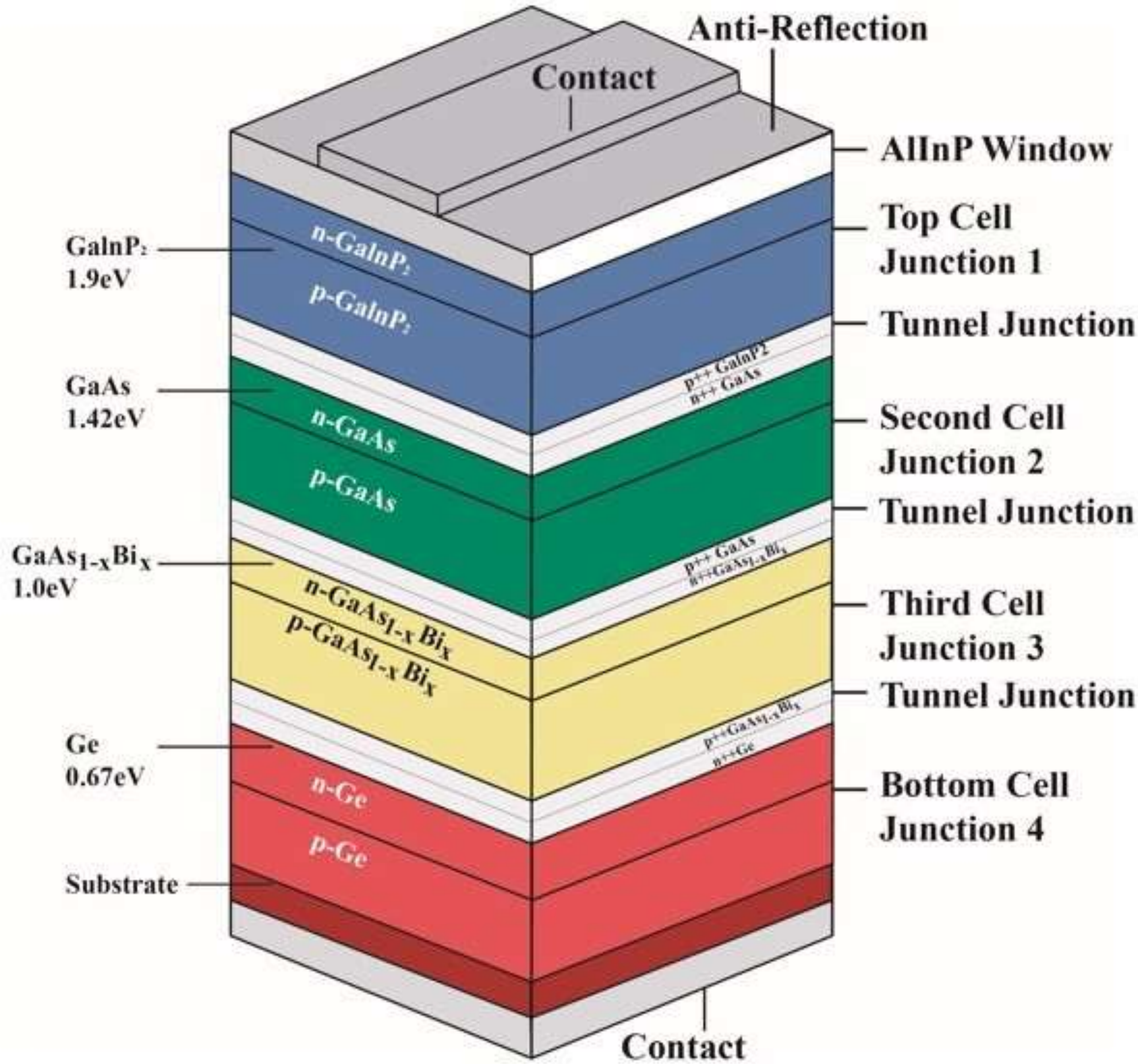

Fig. 2. A schematic design of $GaInP_2/GaAs/GaAs_{0.94}Bi_{0.06}/Ge$ multijunction solar cell.

3. Theoretical Model

In multijunction solar cell, solar spectrum is usually split in parts and each part of spectrum is absorbed in the sub-cells suitable bandgap. It has been already described that sub-cells are stacked in order of higher bandgap to lower bandgap and all these are connected in series. In our present model, we assume that series resistance is zero and shunt resistance is infinity. However, the electrical characteristics of four junction solar cell have been determined using a modified version of the standard equations [12-22]. According to this model, the short-circuit current density (J_{sc}), has been determined directly from ASTM reference spectra (see Figure-3) [23, 24].

$$J_{sc} = \mathrm{e} \times \frac{\lambda I}{hv} \quad (1)$$

Here, e is the electronic charge, I is the irradiance and λ is the wavelength of incident light, h is the Plank constant and v is the velocity of light. For concentrator solar cell, intensity of incoming irradiance (I) is increased by integer multiplication of concentrator factor (C), so the short-circuit current density J_{sc} equation is modified by incorporating an additional concentrator factor (C) with the equation (1).

$$J_{sc} = \mathrm{e} \times \frac{\lambda (C) I}{hv} \quad (2)$$

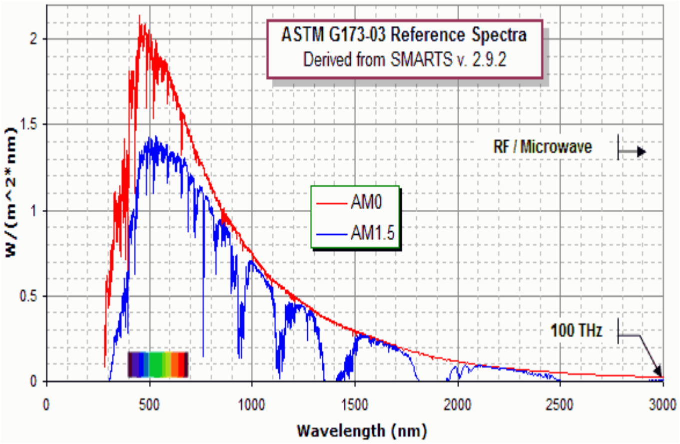

Fig. 3. ASTM G173-03 standard reference spectra [24].

The reverse saturation current density $J_{0,}$ is very important factor for cell performance that is determined for each cell as the sum of the currents for the n-type and p-type layers [14].

$$J_0 = e\left(\frac{D_e}{\tau_e}\right)^{\frac{1}{2}} \frac{n_i^2}{N_A}\left(\frac{S_e\left(\frac{\tau_e}{D_e}\right)^{\frac{1}{2}} cosh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)+sinh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)}{S_e\left(\frac{\tau_e}{D_e}\right)^{\frac{1}{2}} sinh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)+cosh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)}\right) +$$

$$e\left(\frac{D_h}{\tau_h}\right)^{\frac{1}{2}} \frac{n_i^2}{N_D}\left(\frac{S_h\left(\frac{\tau_h}{D_h}\right)^{\frac{1}{2}} cosh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)+sinh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)}{S_h\left(\frac{\tau_h}{D_h}\right)^{\frac{1}{2}} sinh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)+cosh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)}\right) \quad (3)$$

Here, D_e and D_h stand for diffusion constant for electron and hole respectively, τ_e and τ_h are the minority carrier life time for electron and hole, n_i is intrinsic carrier concentration, N_A and N_D are acceptor and donor concentration, S_e and S_h are the surface recombination velocity of electron and hole, $X_h$andX_p are the thickness of p-layer and n-layer.

The diffusion constants D_e and D_h are calculated from the Einstein's relationship [14]:

$$D_e = \frac{kT\mu_e}{e} \quad (4)$$

$$D_h = \frac{kT\mu_h}{e} \quad (5)$$

Here, μ_e and μ_h are the mobility of electron and hole and k is the Boltzmann constant.

The minority carrier life time τ_e and τ_h are calculated from [14]

$$\frac{1}{\tau_e} = \frac{1}{\tau_{SRH}} + BN_A \quad (6)$$

$$\frac{1}{\tau_h} = \frac{1}{\tau_{SRH}} + BN_D \quad (7)$$

Here, τ_{SRH} is the Shockley-Read-Hall life time and B is the direct band-band recombination co-efficient.

The surface recombination velocities of electron S_e and hole S_h are determined from

$$S_e = \frac{D_e}{L_e} = \frac{D_e}{\sqrt{\tau_e D_e}} = \sqrt{\frac{D_e}{\tau_e}} \quad (8)$$

$$S_h = \frac{D_h}{L_h} = \frac{D_h}{\sqrt{\tau_h D_h}} = \sqrt{\frac{D_h}{\tau_h}} \quad (9)$$

The intrinsic carrier concentration $n_i$is determined from

$$n_i^2 = 4M_c M_v\left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{\frac{3}{2}} exp\left(\frac{-E_g}{kT}\right) \quad (10)$$

Here, E_g is the energy bandgap of the semiconductor, T is the temperature, $M_c$and M_v denote the number of equivalent minima in the conduction band and valance band, m_e^* and m_h^* are the effective mass of electrons and holes respectively.When photon with higher energy than material bandgap E_g impinges upon the top cell, it generates power to the cell output and photon with lower energy is transmitted to lower sub-cell releasing excess energy as heat.

The total current density is given by

$$J = J_0\left(e^{\frac{qv}{KT}} - 1\right) - J_{ph} \quad (11)$$

Here, J_{ph} is the current density of photon.

The maximum power density condition can be achieved when

$dP/dV = 0$

$$\frac{d}{dV}\left[V\left[J_0\left(e^{\frac{qv}{KT}} - 1\right) - J_{sc}\right]\right] = 0 \quad (12)$$

Thus the maximum voltage (Vm) is

$$V_m = V_{oc} - \frac{1}{\beta} ln(1 + \beta V_m) \quad (13)$$

Where, $\beta = \frac{q}{kT}$

Similarly, the maximum current density (Jm) is

$$J_m = J_0 \beta V_m e^{\beta V_m} \cong J_{sc}\left(1 - \frac{1}{\beta V_m}\right) \quad (14)$$

The fill factor F.F is

$$FF = \frac{V_m J_m}{V_{oc} J_{sc}} \quad (15)$$

For concentrator multijunction solar cell, input power density $P_{in}$is increased by integer multiplication of concentrator factor (C), so the standard efficiency equation of efficiency is modified by incorporating an additional concentrator factor (C) as:

$$\eta = \frac{V_{oc} J_{sc} FF}{(C) P_{in}} \times 100\% \quad (16)$$

4. Calculation and Results

To simulate the efficiency of this four junction solar cell, the required optoelectronics parameters of different sub-layers are presented in the following table1. The input power densities have been considered for AM1.5G is 1000W/m^2 under 1 sun condition [24].

Table 1: Optoelectronics parameters for $GaInP_2$/$GaAs$/ $GaAs_{.94}Bi_{.06}$/Ge solar cell at 300K.

Parameter	$GaInP_2$[14] Eg_1 =1.9 eV	$GaAs$ Eg_2 = 1.42 eV	$GaAs_{.94}Bi_{.06}$ Eg_3 = 1 eV	Ge Eg_4 = 0.67 eV
λ	654×10^{-9}m	875×10^{-9}m	1141×10^{-9}m	1775×10^{-6}m
M_c	1	1	1	1
M_v	3	1	1	1
μ_e	4000(cm^2/Vs)	2322(cm^2/Vs) [25]	1400(cm^2/Vs)[25]	3900 (cm^2/Vs)[18]
μ_h	200 (cm^2/Vs)	200 (cm^2/Vs)[26]	13 (cm^2/Vs) [26]	1900 (cm^2/Vs)[18]
m_e^*/m_e	0.155	0.067 [25]	0.067 [25]	1.64 [18]
m_h^*/m_h	0.460	0.473 [26]	0.51[26]	0.28 **[17]**
τ_{SRH}	10^{-5} (s)	10^{-5} (s)	10^{-5} (s)	10^{-5} (s)
B	7.5×10^{-10}(s^{1}cm^3)	7.5×10^{-10}(s^{-1}cm^3)	7.5×10^{-10}(s^{-1}cm^3)	7.5×10^{-10}(s^{-1}cm^3)
N_A	10^{17}/ cm^3	9×10^{17}/ cm^3 [25]	3.3×10^{17}/ cm^3[25]	10^{17} /cm^3**[17]**
N_D	2×10^{18}/ cm^3	7.8×10^{17}/cm^3[26]	5.25×10^{17}/ cm^3[26]	$2\times10^{18/}$ cm^3**[17]**
X_n	100×10^{-9} m	100×10^{-9} m	100×10^{-9} m	100×10^{-9} m
X_p	208×10^{-9} m	280×10^{-9} m	3450×10^{-9} m	400×10^{-9} m

The simulations have been performed by using in-house code written for MATLAB software (MathWorks Inc.) and assuming zero losses from series resistance, reflection, grid coverage and tunneling. The optoelectronics parameters of different layers listed in Table 1 were used in the simulation for this cell structure and the output results are shown in Table 2 below.

Table 2. Simulation result for $GaInP_2$ /GaAs /$GaAs_{0.94}Bi_{0.06}$/Ge cell under AM1.5G condition.

Sun Concentration (C)	Open circuit voltage (V_{oc})	Short-circuit current density (Jsc)	Maximum voltage (V_m)	Maximum current density (J_m)	Maximum power (P_m)	Efficiency (η)
1 sun	3.16 (V)	16.43(mA/cm^2)	3.05 (V)	16.29(mA/cm^2)	496.61(W)	49.6%
500 sun	3.81 (V)	8.15×10^3(mA/cm^2)	3.69(V)	8.16×10^3(mA/cm^2)	3.01×10^5(W)	60.2%

For 500 sun concentration, input power density (P_{in}) 1000W/m^2 is increased by 500 times of 1sun illumination. For this reason, simulated result of the short-circuit current density, maximum current density, maximum power output are very high.

5. Discussion

The efficiency of a single junction solar cell is lower due to various loss factors such as reflectance, transmittance, recombination, thermalization loss etc. Generally speaking, multijunction solar cells are to design in a fashion so that most of these loss factors are offset by different sub-layers. By absorbing the entire solar spectrum into the different sub cells, it could overcome the detail balance efficiency limit of single junction solar cell [27]. It has already been mentioned that for achieving ultrahigh efficiency, a 1eV bandgap active semiconductor material $GaAs_{0.94}Bi_{0.06}$ is used as third layer of our proposed multijunction solar cell. In literature, $GaAs_{1-x}Bi_x$ shows very promising results for different optoelectronics properties [25, 26] but for exactly 1eV $GaAs_{0.94}Bi_{0.06}$ layer, there is no certain experimental data available in the literature for effective mass, mobility and doping concentration of electron and hole. Therefore, for theoretical efficiency simulation, the values of these six parameters were optimized in accordance with the reported experimental values of $GaAs_{1-x}Bi_x$ [25, 26]. However, the efficiency of our proposed solar cell has been simulated based on the modified version of spectral p-n junction model [13], using the optoelectronics parameters presented in table 1. Over the years, the spectral p-n junction model was modified for better matching with the optoelectronics properties. For example, Sarah Kurtz *et al.*[14] modified short-circuit current equation for thickness adjustment and reverse saturation current density equation. In our previous works [7, 12], we further modified the reverse saturation current density and surface recombination velocity equation. In this study, we incorporated an additional concentrator factor with both the short-circuit current density and the standard efficiency equation of solar cell. The short-circuit current density is directly related to open circuit voltage, maximum current, maximum voltage and fill-factor. Therefore, incorporating concentrator factor with the short-circuit current density affects the overall cell performance.

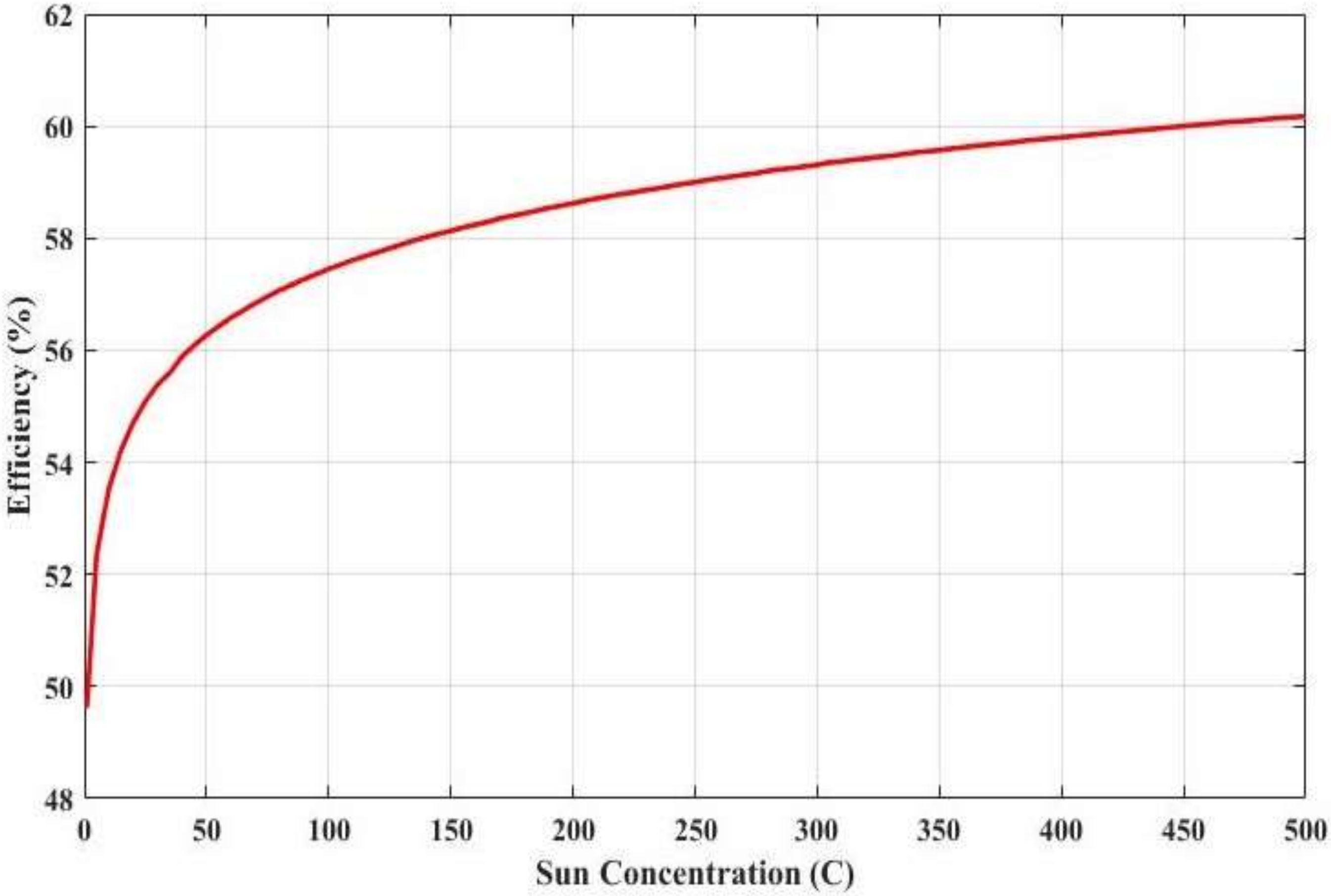

Fig. 4. Sun concentration Vs. Efficiency

Concentrator photovoltaic (CPV) technology has been incorporating with the most of the state-of-the-art terrestrial multijunction solar cells. Usually in CPV, lenses and mirrors focus the concentrated sunlight on a small-area cell and by this way, ultra-high efficiency can be achieved. As mentioned earlier, we incorporated the concentrator factor (C) with the short circuit current density and efficiency equation for efficiency simulation of this CPV. As can been seen from figure 4, the efficiency of CPV is increased rapidly with the initial increase of sun concentration but after 100-sun concentration it slowly reaches to a constant value.

From the simulations, four different short-circuit current densities have been found for four sub-cells. In multijunction solar cell, the lowest current generated in bottom layer and flow through the series connected sub-layers [28], while excess current generated in upper sub-cells radiatively transfer to the lower sub-cells [29, 30]. As these cells are connected in series and all four p-n junctions are in reverse-biased condition, so open circuit voltages of every sub-cell is added to get the total open circuit voltage of the four junction cell [28]. However, open circuit voltage found from the simulation is 3.1686V, where 1eV III-V bismide layer contributed to 0.5764V. In fact, this additional third layer leads to achieve very high theoretical efficiency of 49.6% under 1 sun illumination and an ultra-high efficiency of 60.2% under 500-sun concentration at AM1.5G. The simulation shows that there is a wide variation between efficiencies for 1 sun condition and 500 sun condition. In photovoltaic literature, theoretical efficiencies for concentrating sunlight would be 10-20% higher than that of corresponding 1 sun condition [31] and scientists reported η >60% theoretical efficiencies through different approaches [29]. To date, four junction terrestrial concentrator GaInP/GaAs/GaInAsP/GaInAs solar cell claims the record experimental efficiency of ~ 46 % for four junction solar cell under 504 suns illumination [32].

3. Conclusion

In this work, a 1eV bandgap $GaAs_{0.94}Bi_{0.0583}$ sub-layer is incorporated as the third layer of four junction concentrator photovoltaic cell. The theoretical efficiency of this cell has been evaluated by a modified model and simulations have been performed by using codes written indigenously for MATLAB software (MathWorksInc). The simulated efficiencies of this quadruple junction solar cell were estimated to be 49.6% and 60.2% for AM1.5G solar radiation under 1 sun and 500 sun concentration respectively. From simulated results, it can be concluded that III-V bismide four junction concentrator solar cell shows its promising candidacy for power generation in terrestrial application.

Acknowledgements

Authors would like to thank Professor B M Arora of IIT Mumbai and Professor Zahid Hassn Mahmood of the University of Dhaka for their technical suggestions. This work was financially supported by Ministry of Science and Technology, the People's Republic of Bangladesh under Special Allocation Project (Grant no.: 39.00.0000.09.06.79.2017/ID-418/422, Date: 06.11.2017).

References

[1] S. R. Kurtz, D. Myers, and J. M. Olson, "Projected performance of three-and four-junction devices using GaAs and GaInP," in *Photovoltaic Specialists Conference, 1997., Conference Record of the Twenty-Sixth IEEE*, 1997, pp. 875-878.

[2] D. Friedman, J. Geisz, S. R. Kurtz, and J. Olson, "1-eV solar cells with GaInNAs active layer," *Journal of Crystal Growth*, vol. 195, pp. 409-415, 1998.

[3] D. Friedman and S. R. Kurtz, "Breakeven criteria for the GaInNAs junction in GaInP/GaAs/GaInNAs/Ge four-junction solar cells," *Progress in Photovoltaics: Research and Applications*, vol. 10, pp. 331-344, 2002.

[4] S. Michael and A. Bates, "The design and optimization of advanced multijunction solar cells using the Silvaco ATLAS software package," *Solar energy materials and solar cells*, vol. 87, pp. 785-794, 2005.

[5] D. Friedman, J. Geisz, A. Norman, M. Wanlass, and S. Kurtz, "0.7-eV GaInAs junction for a GaInP/GaAs/GaInAs (1eV)/GaInAs (0.7 eV) four-junction solar cell," in *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on*, 2006, pp. 598-602.

[6] M. J. Hossain, B. Tiwari, and I. Bhattacharya, "Novel high efficiency quadruple junction solar cell with current matching and quantum efficiency simulations," *Solar Energy*, vol. 139, pp. 100-107, 2016.

[7] S. N. Sakib, S. P. Mouri, Z. Ferdous, M. Z. Rahman, and M. S. Kaiser, "Comparison of theoretical efficiencies of three and four layer multijunction solar cell and the effects of varying the bottom layer material," in *Informatics, Electronics and Vision (ICIEV), 2016 5th International Conference on*, 2016, pp. 995-1000.

[8] S. Khanom, M. K. Hossain, F. Ahmed, M. A. Hossain, A. Kowsar, and M. Rahaman, "Simulation study of multijunction solar cell incorporating GaAsBi," in *Humanitarian Technology Conference (R10-HTC), 2017 IEEE Region 10*, 2017, pp. 432-435.

[9] S. Tixier, M. Adamcyk, T. Tiedje, S. Francoeur, A. Mascarenhas, P. Wei, *et al.*, "Molecular beam epitaxy growth of GaAs 1− x Bi x," *Applied physics letters*, vol. 82, pp. 2245-2247, 2003.

[10] S. Francoeur, M.-J. Seong, A. Mascarenhas, S. Tixier, M. Adamcyk, and T. Tiedje, "Band gap of GaAs 1− x Bi x, 0< x< 3.6%," *Applied physics letters*, vol. 82, pp. 3874-3876, 2003.

[11] J. Yoshida, T. Kita, O. Wada, and K. Oe, "Temperature dependence of GaAs1-xBix band gap studied by photoreflectance spectroscopy," *Japanese journal of applied physics*, vol. 42, p. 371, 2003.

[12] A. Kowsar, K. R. Mehzabeen, M. S. Islam, and Z. Mahmood, "Determination of the theoretical efficiency of GaInP/GaAs/GaAs1-xBix multijunction solar cell," in *Proc. of the 10th International conf. on fiber optics and Photonics Photonics, India*, 2010.

[13] M. E. Nell and A. M. Barnett, "The spectral pn junction model for tandem solar-cell design," *IEEE Transactions on Electron Devices*, vol. 34, pp. 257-266, 1987.

[14] S. R. Kurtz, P. Faine, and J. Olson, "Modeling of two-junction, series-connected tandem solar cells using top-cell thickness as an adjustable parameter," *Journal of Applied Physics*, vol. 68, pp. 1890-1895, 1990.

[15] M. A. H. Abu Kowsar, Md Sofikul Islam, Afrina Sharmin and Z. H. Mahmood, "Analysis of theoretical efficiencies of GaInP2/GaAs/Ge multijunction solar cell," *The Dhaka University Journal of Applied Science and Engineering*, vol. 3, 2015.

[16] A. Kowsar, A. Y. Imam, M. Rahaman, M. S. Bashar, M. S. Islam, S. Islam, *et al.*, "Comparative study on the efficiencies of silicon solar cell."

[17] S. N. Sakib, S. P. Mouri, Z. Ferdous, A. Kowsar, and M. S. Kaiser, "Effect of different solar radiation on the efficiency of GaInP2/GaAs/Ge based multijunction solar cell," in *Electrical Information and Communication Technology (EICT), 2015 2nd International Conference on*, 2015, pp. 528-532.

[18] S. M. Sze and K. K. Ng, *Physics of semiconductor devices*: John wiley & sons, 2006.

[19] M. I. A Kowsar, KR Mehzabeen, ZH Mahmood, "Study on the Efficiency of the GaInP2/GaAs/Ge Multijunction Solar Cell," in *Proc. of International Conference on Environmental Aspects of Bangladesh,BEN, Japan*, 2010, pp. 116-119.

[20] S. N. Sakib, S. P. Mouri, A. Kowsar, M. Rahaman, and M. S. Kaiser, "Theoretical efficiency of AlAs/GaAs/GaAs0. 91Bi0. 085 based new multijunction solar cell and effects of solar radiation and sun concentration on it," in *Microelectronics, Computing and Communications (MicroCom), 2016 International Conference on*, 2016, pp. 1-6.

[21] A. Hemmani, A. Nouri, H. Khachab, and T. Atouani, "Optimization of the emitter's bandgap and thickness of AlxGa1-xAs/GaAs Multi-junction solar cell," *International Journal of Renewable Energy Research (IJRER),* vol. 7, pp. 525-530, 2017.

[22] A. Dilan, "Quantum photovoltaic effect: Two photon process in solar cell," in *Renewable Energy Research and Applications (ICRERA), 2015 International Conference on*, 2015, pp. 1084-1088.

[23] D. R. Myers, K. Emery, and C. Gueymard, "Revising and validating spectral irradiance reference standards for photovoltaic performance evaluation," *Journal of solar energy engineering,* vol. 126, pp. 567-574, 2004.

[24] A. Standard, "G173,"Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37 Tilted Surface," Amer," *Society for Testing Matls., West Conshocken PA, USA,* 2007.

[25] R. Kini, L. Bhusal, A. Ptak, R. France, and A. Mascarenhas, "Electron hall mobility in GaAsBi," *journal of applied physics,* vol. 106, p. 043705, 2009.

[26] D. Beaton, R. Lewis, M. Masnadi-Shirazi, and T. Tiedje, "Temperature dependence of hole mobility in GaAs 1− x Bi x alloys," *journal of applied physics,* vol. 108, p. 083708, 2010.

[27] W. Shockley and H. J. Queisser, "Detailed balance limit of efficiency of p-n junction solar cells," *Journal of applied physics,* vol. 32, pp. 510-519, 1961.

[28] P. Würfel, *Physics of solar cells* vol. 1: Wiley-vch Weinheim, 2005.

[29] S. Kurtz, D. Myers, W. McMahon, J. Geisz, and M. Steiner, "A comparison of theoretical efficiencies of multi-junction concentrator solar cells," *Progress in Photovoltaics: research and applications,* vol. 16, pp. 537-546, 2008.

[30] A. S. Brown and M. A. Green, "Radiative coupling as a means to reduce spectral mismatch in monolithic tandem solar cell stacks theoretical considerations," in *Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE*, 2002, pp. 868-871.

[31] A. Marti and G. L. Araújo, "Limiting efficiencies for photovoltaic energy conversion in multigap systems," *Solar Energy Materials and Solar Cells,* vol. 43, pp. 203-222, 1996.

[32] M. A. Green, Y. Hishikawa, E. D. Dunlop, D. H. Levi, J. Hohl-Ebinger, and A. W. Y. Ho-Baillie, "Solar cell efficiency tables (version 51)," *Progress in Photovoltaics: Research and Applications*, vol. 26, pp. 3-12, 2018.