Available online at www.most.gov.bd

Volume 04, Issue (1), Page: 37-48, 2022

Ministry of Science and Technology

Government of The People's of Bangladesh
Bangladesh Secretariat, Dhaka.

Modeling and Simulation of Efficiency of Five Junction Solar Cell Using MSCS-1D Simulator

M. A. Rahman[1], M. Hasan[1], A. Kowsar[2]*, S. C. Debnath[2], M. Rahaman[2] and M. L. Palash[1]*

[1]Department of Electrical and Electronic Engineering, University of Dhaka, Dhaka-1000, Bangladesh

[2]Institute of Fuel Research and Development (IFRD), Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhanmondi, Dhaka-1205, Bangladesh

Abstract

The third-generation multijunction solar cell (MJSC) is the most promising solar cell in terms of champion photoconversion efficiency. This advanced photovoltaic solar cell is considered as the future green electricity source to meet the gradually increasing terrestrial energy demand. Usually, MJSC consists of 2 to 6 semiconducting materials. These materials work as the sub-cells or sublayers in a multijunction solar cell. This sub-cell is selected in a fashion so that it can absorb the entire solar spectrum. In this project, the efficiency of a novel solar cell has been investigated. A detailed analysis of each sub-cell has been done using the state-of-the-art MSCS-1D simulation software. The materials of each sub-cell of the solar cell have been selected so that they can efficiently utilize the entire ultraviolet to infrared spectrum. The optoelectronic parameters used in the simulation were collected from the standard references. The photoconversion efficiency of this model is simulated to be 48.29% and 59% for AM1.5G solar radiation under one sun and 500 sun conditions, respectively. These simulation results will assist in realizing the performance of the 5-junction solar cell in practical fabrication.

Received: 28.08.2022

Revised: 27.03.2023

Accepted: 10.05.2023

DOI: https://doi.org/10.3329/jscitr.v4i1.67367

Keywords: Photovoltaic; Multijunction Solar Cell; MSCS-1D; Simulation; Efficiency.

Introduction

Energy is crucial for the advancement of modern civilization as it powers the technological and industrial processes that drive economic growth and social progress (Zou *et al.,* 2022). Without access to reliable and affordable energy, many of the systems and services that we rely on, such as transportation, communication, healthcare, and manufacturing, would not be able to function at the level they do today. Furthermore, energy is essential for the global economy as it is needed for economic development, infrastructure, and job creation. Since the discovery of fossil fuels around the world, development has become faster to faster for most countries (Chow *et al.,* 2003). Access to energy is also essential for achieving key global sustainable development goals, such as reducing poverty and improving health and education outcomes. But the minable fossils are gradually decreasing with the increase in demand leading to a crisis of this de facto development weapon (Dingbang *et al.,* 2021; Kowsar *et al.,* 2022).

*Corresponding author's e-mail: apukowsar@gmail.com; mlpalash@du.ac.bd

Moreover, artificial phenomena, such as wars between nations, might deepen the crisis. In addition, another big player named greenhouse gas that emerged during the burning of fossil fuels and affects the total socio-economic, environmental, and geopolitical ecosystem. (Kowsar *et al.,* 2022). This increases the global warming, leading to a drastic change in the climate of most of the regions of the earth. So, the insufficiency of the minable fossil fuels and the derivate produced during the burning of these fossil fuels force global leaders, policymakers, and scientists way out the alternative energy sources (Islam *et al.,* 2022; Rahaman *et al.,* 2020). Hence, renewable energy technologies meet-up the demand arising from both aforementioned factors. Among the renewable sources, solar photovoltaic (PV) source is the most optimal solution for the nations, especially for those who do not have enough hydro, wind, or tidal sources for power generation. Solar PVs can be utilized in two ways. Firstly, green electricity from low-cost technology can be generated. In this case, usually single junction silicon and thin-film solar cell undoubtedly occupy the space, but the sources are lower efficient (Shah *et al.,* 1999). Secondly, large power can be obtained from this technology using a small area. For this case, the multijunction solar cell is the only option among PV classifications, and in fact, this source is capable of generating roughly two times higher energy comparatively single-junction solar cells (Green *et al.,* 2021). Prominent PV electricity-generating countries like China, India, the USA, etc., use their thousands of acres of uncultivated land for such energy production by using single junction silicon or thin-film solar cell (Hosen *et al.,* 2020; Ushasree & Bora, 2019). Bangladesh, the great Ganges delta, the most climate-vulnerable country and the most densely populated country in the world, has 165 million populations living within a 148,460 square kilometres boundary (Rahaman *et al.,* 2021). The country is blessed with 95% agricultural land but does not possess salty barren lands or deserts for PV electricity generation. Moreover, as silicon or thin-film solar cells possess comparatively lower photoconversion efficiency, ultra-high efficient multijunction solar cells would be the best selection for clean electricity generation.

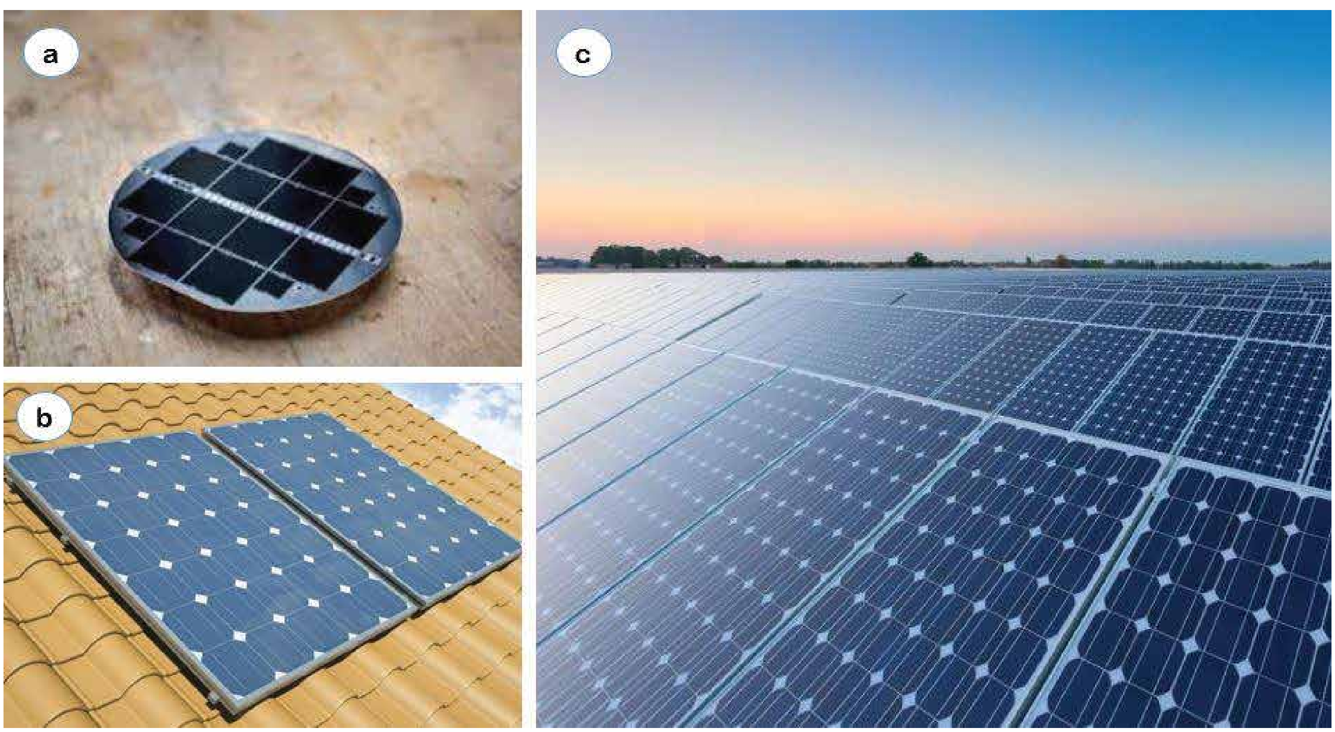

Fig. 1. (a) Multijunction solar cell, (b) multijunction solar panel, (c) photovoltaic power plant comprising with multijunction solar panel (Cariou *et al.,* 2018).

In practical cases, MJSCs are used in extra-terrestrial sophisticated applications such as satellites, space stations, space vehicles, etc. (Komerath & Komerath, 2011). As this type of solar cell belongs to an extremely tough environment, so these solar panels are comprised of very high-quality compound semi-conductor materials that make the manufacturing cost significantly higher than the single junction solar panels (Dimroth, 2006). However, due to its higher electricity generation capability from comparatively small areas, researchers are focusing on the development of this advanced PV solar cell for terrestrial application using comparatively low-quality material for cost-effective power production. Multijunction solar cells are promising because they have the ability to convert a broader range of the solar spectrum into electricity, resulting in higher conversion efficiencies. In single-junction solar cells, only a narrow range of the solar spectrum can be converted into electricity, resulting in lower conversion efficiencies. In addition, multijunction solar cells can operate at higher temperatures without a significant loss in efficiency, making them well-suited for use in space and high-temperature terrestrial environments. Fig. 1 presents the multijunction solar cell, panel, and power plant.

III-V concentrator multijunction cells are the most efficient solar cells currently available, making them an attractive option for concentrated photovoltaic (CPV) systems. Their Efficiency rates range from over 40% in recent years to 60% (King *et al.,* 2012). The volume of the material required for cell fabrication is greatly reduced by this CPV technology that lowers the cost of the solar cell. Concentrator multijunction solar cells are made for terrestrial applications (Kowsar & Farhad, 2018). A MJSC is made up of some sub-cell junctions or layers, each of which is designed to absorb and transform a specific amount of solar energy into electricity (Hossain *et al.,* 2016a). Photons of a certain energy level are blocked by each sub-cell layer, while the lower energy photons are passed on to the next layer. The series-connected sub-cells create a higher voltage output compared to the single junction cell. The overall efficiency of the cell can be improved by making use of the highest photovoltaic conversion capacities of each individual sub-cell (Leite *et al.,* 2013). Depending on the bandgap of the material, a multijunction solar cell absorbs different amounts of energy from different parts of the electromagnetic spectrum. When the MJSC exposed to high-energy photons, sub-cells with higher bandgap will produce more voltages per unit area materials with lower bandgaps tend to absorb low-to-high energy photons and yield lower voltages but higher currents. When designing a multijunction solar cell, the selection of the right combination of materials with high and low bandgaps is crucial. In order to reduce the threading dislocations, that lower the open circuit voltage, the adjacent cells must also be latticematched, which can be a challenging task (Patel *et al.,* 2012). Some technologies allow lattice mismatch to a certain extent. Solar cells are an effective renewable energy resource. Unfortunately, higher conversion efficiency and affordability have been the key concerns (Hossain *et al.,* 2016b). With an infinite number of junctions, a multijunction solar cell theoretically offers a maximum of 86.4% conversion efficiency (Yamaguchi and Luque, 1999). In 1997, a four-layered GaInP/GaAs/(not specified)/Ge multijunction solar cell was developed by Sarah Kurtz *et al.* (King *et al.,* 2002) that could theoretically reach an efficiency of 50%.

Due to the massive potential of generating very high photoconversion efficiency, MJSC already draws concentration to the researchers. It has already been mentioned earlier that up to four-junction MJSCs are found in the literature. Nevertheless, there is scant information about the numerical simulation or practical demonstration of the five-junction MJSCs. Therefore, the article aims to model a novel combination of five-junction solar cell and investigate the photoconversion efficiency using an advanced version of the multijunction solar cell simulator, MSCS-1D. The cell combination incorporated a 1.08 eV bandgap

InGaAs material in its third sub-layer to form the new combination GaInP2/GaAs/InGaAs/GaAs0.94-Bi0.06/Ge solar cell. The simulation has been performed to evaluate the key solar cell parameters under the normal atmospheric condition (AM1.5G) as well as concentrating CPV condition. The photoconversion efficiency of the solar cell has been estimated as 48.29% and 51.24%, respectively, for airmass AM1.5G global and AM1.5D direct normal conditions. The simulation procedure is further extended to 500 suns concentrating conditions. As a result, a linear rise in the short-circuit current of around 10% is caused by the high concentration factor.

Materials and Methods

The conversion efficiency of solar panels or the solar cells can be increased significantly by incorporating different bandgap materials as the sub-cell of MJSC that absorb each part of the incident solar spectrum separately. In fact, using this technique, the Shockley-Queisser limit (Markvart, 2022) for the efficiency of single junction cells can be overcome (Khanom *et al.,* 2018). Keeping this principle in mind, the proposed 5-junction solar cell has been investigated. The schematic arrangement of the proposed cell is shown in Fig. 2.

When photons penetrate a material, they are partially absorbed as they travel through the material. If the photon's energy exceeds the bandgap threshold of the semiconductor, it can break chemical bonds and excite an electron from one level to another, creating an imbalance between electrons in two different

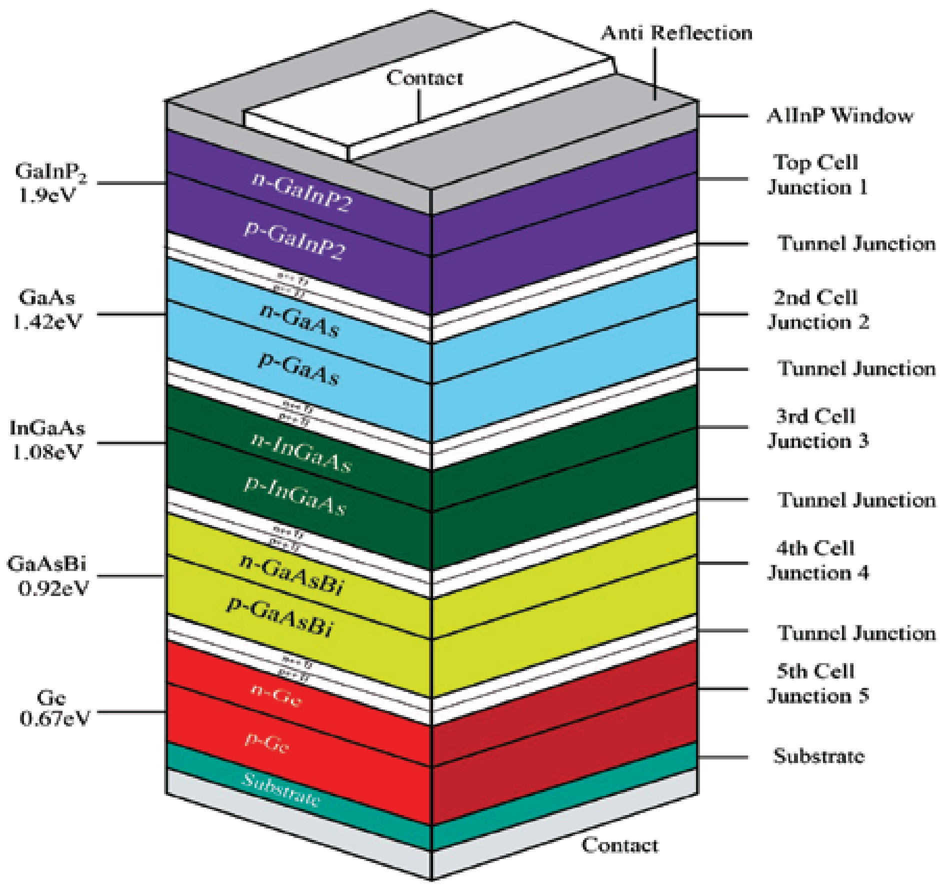

Fig. 2. Schematic arrangement of the proposed multijunction solar celladopted with reference (Kowsar & Farhad, 2018).

bands; thus, creating electrically charged particles called electron-hole pairs. Low-bandgap materials provide greater current density but lower open circuit voltage (V_{oc}) while high-bandgap materials provide higher V_{oc} but lower short-circuit current density (J_{sc}). Usually, V_{oc} remains lower compared to the bandgap

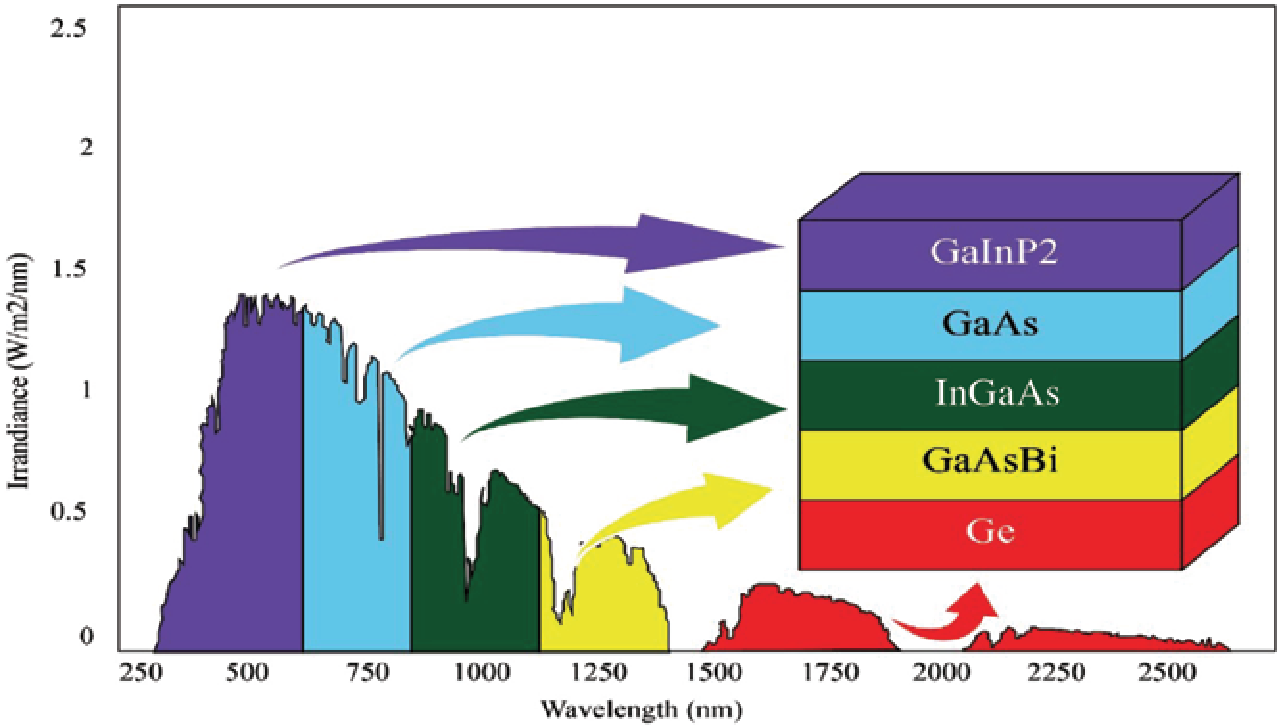

Fig. 3. Different junctions absorb a different portion of solar radiation adopted with reference (Khanom *et al.,* 2018).

Table 1. Optoelectrical Parameters of $GaInP_2/GaAs/InGaAs/GaAs_{0.94}Bi_{0.06}/Ge$ solar cell at 300k.

Parameter	$GaInP_2$ Eg_1 =1.9 eV	GaAs Eg_2 = 1.42 eV	InGaAs Eg_3 = 1.08 eV	$GaAs_{0.94}Bi_{0.06}$ Eg_4 = 0.92 eV	Ge Eg_5 = 0.67 eV
λ (m)	654×10^{-9}	875×10^{-9}	115.0347×10^{-8}	1141×10^{-9}	1775×10^{-6}
M_c	1	1	1	1	1
M_v	3	1	1	1	1
μ_e (cm^2/Vs)	4000	2322	8510	1400	3900
μ_h (cm^2/Vs)	200	200	3.48	13	1900
m_e^*/m_e	0.155	0.067	0.043	0.067	1.64
s	0.460	0.473	0.460	0.51	0.28
τ_{SRH} (s)	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}
B ($s^{-1}cm^3$)	7.5×10^{-10}	7.5×10^{-10}	7.5×10^{-10}	7.5×10^{-10}	7.5×10^{-10}
N_A (cm^{-3})	10^{17}	9×10^{17}	5×10^{16}	3.3×10^{17}	10^{17}
N_D (cm^{-3})	2×10^{18}	7.8×10^{17}	8.5×10^{18}	5.25×10^{17}	2×10^{18}
X_n (m)	100×10^{-9}	100×10^{-9}	70×10^{-9}	100×10^{-9}	100×10^{-9}
X_p (m)	208×10^{-9}	280×10^{-9}	1870×10^{-9}	3450×10^{-9}	400×10^{-9}

voltage E_g of that semiconductor material. For series connected MJSC, the J_{sc} generated from different sub-cells need to match with each other to obtain higher conversion efficiency.

The proposed 5-junction model with a top cell $GaInP_2$ having a bandgap of 1.9 eV is a high-quality material, capable to absorb the ultraviolet portion of the solar spectrum. For the 2nd junction, another high-quality material, GaAs with 1.42 eV bandgap has been selected, which is good for absorbing the visible range solar spectrum.

From Fig. 3, it has been seen that solar spectrum radiation has peak irradiance in the visible range, thus, GaAs will generate both high current and high voltage. To utilize other portions of the solar spectrum, the In GaAs semiconductor is used as the 3rd junction, having a bandgap energy of 1.08 eV, which will absorb the near-infrared part. As infrared has the highest range of all other solar spectrums, the combination needs other materials to absorb mid-infrared sections properly. So, a novel compound has been formed from the

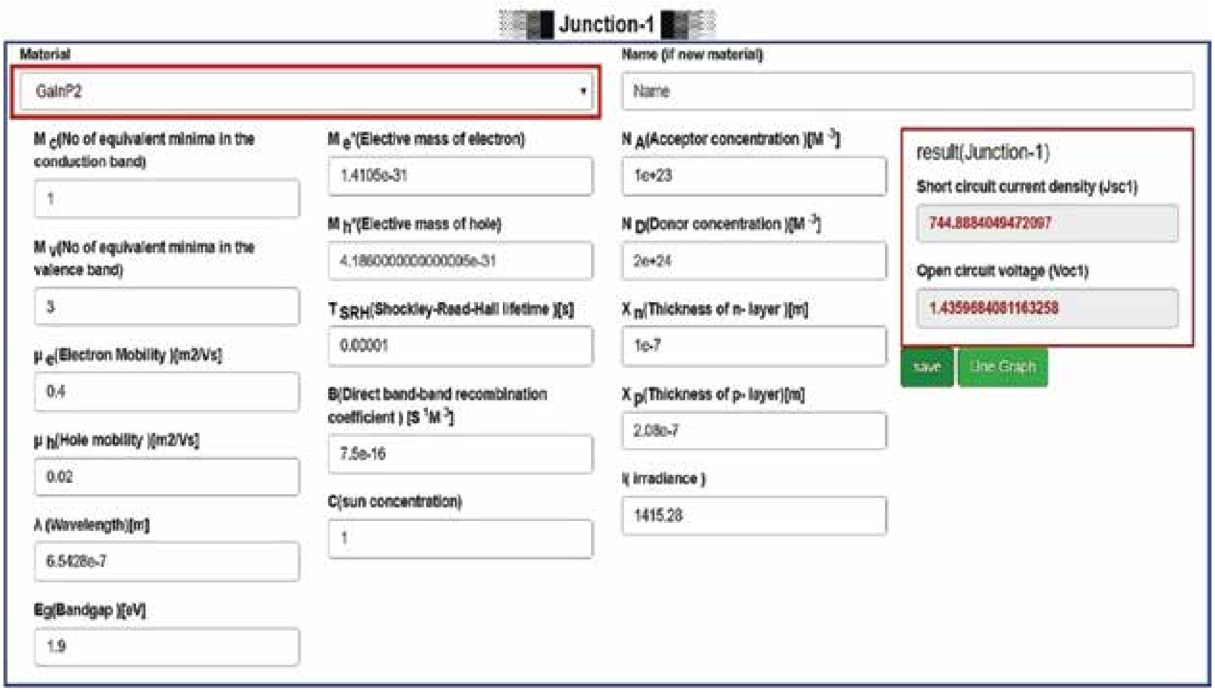

Fig. 4. Filled dialog box with proper optoelectronic parameters for the first junction.

mixture of GaAs with Bismide (Bi), which makes a bowing of bandgap of GaAs depending on the Bi content (percentage). $GaAs_{0.94}Bi_{0.06}$ combination creates a bandgap of 0.92 eV, which is appropriate for the concerned multijunction solar cell model. Lastly, the Ge is selected as the bottom layer having a bandgap energy of 0.67eV, which facilitates to absorption rest of the infrared portion. We use light management to split light so that the cell's short circuit current density matches.

The optoelectronic properties for the sub-cells or sublayers of the considered five junction solar cell $GaInP_2/GaAs/InGaAs/GaAs_{0.94}Bi_{0.06}/Ge$ has been collected from (Kowsar *et al.,* 2020), is shown in table 1. These parameters have been utilized for simulating each junction using the MSCS-1D tool (Kowsar *et al.,* 2021). The MSCS-1D simulation software is developed based on the modified spectral p-n junction model for MJSCs (Kowsar *et al.,* 2018; Kowsar *et al.,* 2018, 2019). The input intensity power is $1000 W/m^2$ for AM1.5G global radiation.

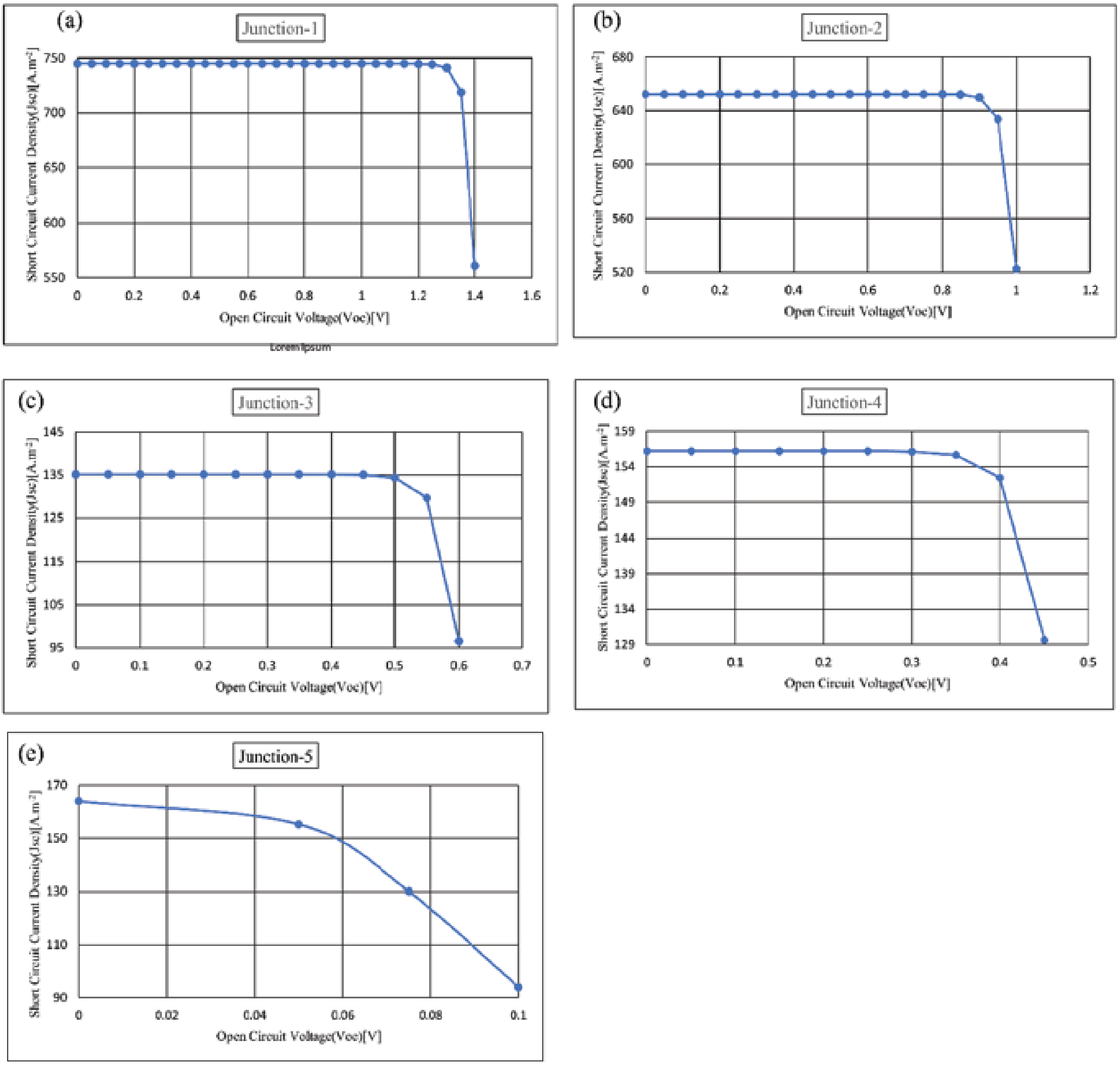

Fig. 5. The J_{sc} vs. V_{oc} characteristics curves for all five sub-cellsof the multijunction solar cell, where figures(a) to (e) representsthe curves for top sub-cellto the bottom sub-cell.

The simulation has been performed for the normal sun condition (1 sun condition) to the concentrating condition (up to 500 sun conditions). The top junction consists of $GaInP_2$ filled with proper optoelectronic parameters. The dialog box for the first junction of MSCS-1D is shown in Fig. 4.

All the input optoelectronic properties for $InGaP_2$ have been inserted into the dialog box of MSCS-1D and, after simulating the top junction, the short circuit current density (J_{sc1}) and open circuit voltage (V_{oc1}) has been determined. Due to higher bandgap energy, $InGaP_2$ absorbs the ultraviolet to the visible spectrum of

Table 2. Summary of the simulation for each junction.

	$GaInP_2$ 1st junction	GaAs 2nd junction	InGaAs 3rd junction	$GaAs_{0.94}Bi_{0.06}$ 4th junction	Ge 5th junction
V_{oc}(V)	1.436	1.042	0.632	0.495	0.122
J_{sc}(mA/cm^2)	74.489	65.239	13.514	15.621	16.397

Table 3. Simulation result for $GaInP_2$/GaAs/InGaAs/$GaAs_{0.94}Bi_{0.06}$/Ge cell under 1 sun condition

Air Mass	Open circuit Voltage, V_{oc} (V)	Short-circuit current density, J_{sc} (mA/cm^2)	Maximum Voltage, V_m (V)	Maximum current density, J_m (mA/cm^2)	Efficiency η (%)
AM1.5G	3.727	13.514	3.599	13.417	48.29
AM1.5D	3.719	12.933	3.592	12.84	51.24

sunlight irradiance and generated higher J_{sc1} and V_{oc1}. Using the similar procedure, otherJ_{sc} and V_{oc} have been simulated for the other four sub-cells. The characteristicscurrent-voltage (J_{sc}vs. V_{oc}) graph can be generated using the advanced software package. For all five sub-cells of the $GaInP_2$/GaAs/InGaAs/$GaAs_{0.94}Bi_{0.06}$/Ge, the J_{sc}vs. V_{oc} characteristics curves have been shown in Figure 5. The characteristics curve (J_{sc}vs. V_{oc}) for each junction has been generating using the MSCS-1D software.

Results and Discussion

The junctions are connected in series so that the same current will flow through the all 5 sub-cells of the solar cell. The lowest current of these junctions will flow through the five-junction solar cell. The rest of the current will be wasted as heat. So, this current mismatching limit the efficiency of a solar cell. Simulation is performed assuming standard test conditions (the input power is 1000W/m^2 at 300K temperature). After the simulation run, the total short circuit current density, open circuit voltage and the efficiency have been obtained. Table 2 presents a brief description of this simulation.

However, the solar cell's input power performance will increase if concentrated solar power is used. The efficiency has been estimated to 48.29% for 1 sun condition, increasing to 59% for 500 sun conditions under the AM1.5G solar radiation spectrum. Input power to the model has been increased by 500x for calculating efficiency under 500 sun conditions.

When sunlight travels through the atmosphere, it is partially scattered. The one thing determining how much direct sunlight reaches the ground is how far it travels before getting to the surface. The ratio of actual travel length and the minimum length is called Air mass. The efficiency of the solar cell also varies with different air mass conditions. Table 3 shows the efficienciesand other performance parameters at different air masses conditions. Previously, researchers proposed a novel $GaInP_2$/GaAs/$GaAs_{0.94}Bi_{0.06}$/Ge four junction solar cell that had achieved 49.6% efficiency (Kowsar & Farhad, 2018). Adding In GaAs band gap of 1.08eV as the third layer increases the infrared absorption, making the solar cells more powerful and the efficiency has reached at 51.24% for AM 1.5D.

We have simulated the efficiency of our proposed solar cell in MSCS-1D, which is based on the modified spectral p-n junction model. In the MSCS-1D, four out of five junction optoelectronic parameters were given built-in. There was no such specification for the third sub-cell, so we had to figure it out for ourselves to run the simulation. Open circuit voltage, fill factor, maximum voltage and current, etc. are only a few of the variables that are associated with short-circuit current density. The mentioned short-circuit current density can be affected by the concentration of light as it enters through a photovoltaic cell by considering the concentrator factor. Thus, as we see from the figure, the efficiency increases proportionally when we increase the concentrated factor. Some modern applications of multijunction solar cells in terrestrial use have been employed with CPV.

In order to escalate the solar cell conversion efficiency, CPV typically uses reflectors (mirrors) and lenses to concentrate strong sunlight onto a particular location Thus, we increase the concentrator factor to see the feasibility of our proposed multijunction solar cell for terrestrial application. As expected, increased efficiency is found using increasing concentration factors. Four different currents have been measured from simulations of the solar cells. In a multijunction solar cell, the lowest current flows through the series connection of sub-cells on the bottom layer. In contrast, surplus currents are drained off by radiative transfer to other layers (Würfel, 2016)(Kurtz et al., 2008).The sum of the open circuit voltages produced by each cell will make up the total open circuit voltage because the five sub-cells are interconnected in series and all of the junctions are reverse biased (Würfel & Würfel, 2016). The added extra layer of InGaAs on the third sub-cell contributes 0.63V open circuit voltage. Adding this voltage to the other four cells increases the overall output to 3.727 V, increasing our solar cell's voltage and efficiency. However, the simulated efficiencies for the 5-junction solar cell are higher, but these are in the upper boundary 55.1% for AM 1.5 G and 71.1% for AM 1.5D condition for the 5-junction ideal MJSCs (Green, 2006), and simulated efficiencies are decent near to the champion 47.1% experimental efficiency that is recently reported in *Nature Energy* (Geisz et al., 2020). So, the MSCS-1D simulated results and photoconversion efficiencies of the modeled combination could assist the manufacturers in fabricating solar cells efficiently. As the modeled combination consists of three comparatively low-quality materials than GaAs and $GaInP_2$, the per-watt cost of the MJSCs surely be reduced, and if CPV technology is used with the MJSC, the efficiency might be increased that trade-off the overall price of the solar cells.

Conclusions

In this work, 1.08eV bandgap InGaAs material has been incorporated as the third sub layer of a new combination five-junction $GaInP_2$/GaAs/InGaAs/$GaAs_{0.94}Bi_{0.06}$/Ge solar cell. State-of-the-art simulator, MSCS-1D has been used to evaluate the performance of this solar cell. The photoconversion efficiency of the solar cell has been estimated as 48.29% and 51.24%, respectively, for airmass AM1.5G global and AM1.5D direct normal conditions. The newly incorporated InGaAs contributed to 0.63V open-circuit voltage in an overall 3.727V open-circuit voltage, which in turn helps boost the performance of the solar cell for both atmospheric conditions. The MSCS-1D simulated results will offer the manufacturers to fabricate the solar cells efficiently, cost-effectively for the terrestrial,industrial, and residential applications.

Acknowledgments

The Ministry of Science and Technology (MoST), the People's Republic of Bangladesh provided the financial assistance for this work under its Special Allocation Scheme (Grant number: 39.00.0000.09.06.009.20-1331/EAS-402; ID: EAS-402, Date: 08.12.2020). The authors want to thank the MoST Bangladesh for their support.

Data availability

All data generated or analyzed in this study are available from the authors on request.

Conflicts of interest

The authors declare that they have no competing interests.

References

Cariou R, Benick J, Feldmann F, Höhn O, Hauser H, Beutel P, Razek N, Wimplinger M, Bläsi B, Lackner D, Hermle M, Siefer G, Glunz, S. W, Bett AW and Dimroth F 2018. III–V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration. *Nature Energy* **3**(4): 326–333. https://doi.org/ 10.1038/s41560-018-0125-0

Chow J, Kopp RJ and Portney PR 2003. Energy Resources and Global Development. *Science* **302**(5650): 1528–1531. https://-doi.org/10.1126/science.1091939

Dimroth F 2006. High-efficiency solar cells from III-V compound semiconductors. *Physica Status Solidi C* **3**(3): 373–379. https://doi.org/10.1002/PSSC.200564172

Dingbang C, Cang C, Qing C, Lili S and Caiyun C 2021. Does new energy consumption conducive to controlling fossil energy consumption and carbon emissions?-Evidence from China. *Resources Policy* **74:** 102-427. https://doi.org/10.1016/j.resourpol.2021.102427

Geisz JF, France R M, Schulte KL Steiner M A, Norman AG, Guthrey HL, Young MR, Song T and Moriarty T 2020. Six-junction III–V solar cells with 47.1% conversion efficiency under 143 Suns concentration. *Nature Energy.* **5**(4): 326–335. https://doi.org/10.1038/s41560-020-0598-5

Green MA, Dunlop ED, Hohl-Ebinger J, Yoshita M, Kopidakis N and Hao X 2021. Solar Cell Efficiency Tables (Version 58). *Progress in Photovoltaics: Research and Applications*, **29**(7): 657–667. https://doi.org/10.1002/PIP.3444

Green MA 2006. *Third Generation Photovoltaics*. https://doi.org/10.1007/B137807

Hosen MB, Ali MK, Asaduzzaman M, Kowsar A and Bahar AN 2020. Performance Optimization of ZnS/CIGS Solar Cell With Over 25% Efficiency Enabled by Using a CuIn3Se5 OVC Layer. *International Journal of Renewable Energy Research* **10**(4): 2000–2005. https://doi.org/10.20508/ijrer.v10i4.11430.g8100

Hossain MJ, Tiwari B and Bhattacharya I 2016a. Novel high efficiency quadruple junction solar cell with current matching and quantum efficiency simulations. *Solar Energy*, **139:** 100–107. https://doi.org/10.1016/j.solener.2016.09.031

Hossain MJ, Tiwari B and Bhattacharya I 2016b. An adaptive step size incremental conductance method for faster maximum power point tracking. *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 3230–3233. doi: 10.1109/PVSC.2016.7750262

Islam MMM, Kowsar A, Haque AKMM, Hossain MK, Ali MH, Rubel MHK and Rahman MF 2022. Techno-economic Analysis of Hybrid Renewable Energy System for Healthcare Centre in Northwest Bangladesh. *Process Integration and Optimization for Sustainability*, **1:** 1–14. https://doi.org/10.1007/S41660-022-00294-8

Khanom S, Hossain M K., Ahmed, F., Hossain, M. A., Kowsar, A and Rahaman, M. 2018. Simulation study of multijunction solar cell incorporating GaAsBi. *5th IEEE Region 10 Humanitarian Technology Conference 2017, R10-HTC 2017*, *2018-Janua*. https://doi.org/10.1109/R10-HTC.2017.8288992

King, R. R., Bhusari, D., Larrabee, D., Liu, X., Rehder, E., Edmondson, K., Cotal, H., Jones, R. K., Ermer, J. H., Fetzer, C. M., Law, D. C., & Karam, N. H. 2012. *Solar cell generations over 40 % ef fi ciency*. https://doi.org/10.1002/pip

King, R. R., Colter, P. C., Joslin, D. E., Edmondson, K. M., Krut, D. D., Karam, N. H and Kurtz, S. 2002. *High-Voltage , Low-Current GaInP / GaInP / GaAs / GaInNAs / Ge Solar Cells*. DOI: 10.1109/PVSC.2002.1190713

Komerath, N. M and Komerath, P. P. 2011. Terrestrial Micro Renewable Energy Applications of Space Technology. *Physics Procedia*, **20:** 255–269. https://doi.org/10.1016/J.PHPRO.2011.08.024

Kowsar, A., Farhad, S. F. U and Sakib, S. N. 2018. Effect of the bandgap, sun concentration and surface recombination velocity on the performance of a III-V bismide multijunction solar cells. *International Journal of Renewable Energy Research*, **8**(4): doi: https://doi.org/10.20508/ijrer.v8i4.8579.g7526

Kowsar, A., Sakib, S. N., Billah, M., Dey, S., Babi, K. N., Bahar, A. N and Farhad, S. F. U. (2020). A novel simulator of multi-junction solar cells-MSCS-1D. *International Journal of Renewable Energy Research*, **10**(3): doi: https://-doi.org/10.20508/ijrer.v10i3.11147.g8012

Kowsar, A, Billah, M., Dey, S., Debnath, S. C., Yeakin, S and Uddin Farhad, S. F. 2019. Comparative Study on Solar Cell Simulators. *ICIET 2019 - 2nd International Conference on Innovation in Engineering and Technology*. https://-doi.org/10.1109/ICIET48527.2019.9290675

Kowsar, A, Debnath, S. C., Islam, M. S., Bahar, A. N., & Farhad, S. F. U. (2021). Numerical Simulation of the High Efficiency Triple Junction Concentrator Photovoltaic Cells Using MSCS-1D. *Conference Record of the IEEE Photovoltaic Specialists Conference*, 722–725. https://doi.org/10.1109/PVSC43 889.2021. 9518975

Kowsar, A and Farhad, SFU 2018. High Efficiency Four Junction III-V Bismide Concentrator Solar Cell: Design, Theory, and Simulation. *International Journal of Renewable Energy Research (IJRER)*, **8**(3): 1762–1769, doi: https://-doi.org/10.20508/ijrer.v8i3.7982.g7477

Kowsar, A, Haque, N., Islam, M. S., Debnath, S. C., Rahaman, M and Alam, F. (2022). Techno-economic evaluation of a 29-kW micro-grid hybrid photovoltaic system for a healthcare center in Bangladesh. *AIP Conference Proceedings*, **2681**(1): 020071. https://doi.org/10.1063/5.0118023

Kowsar, A., Nazmus Sakib, S and Farid Uddin Farhad, S., (2018). Effect of the Bandgap, Sun Concentration and Surface Recombination Velocity on the Performance of a III-V Bismide Multijunction Solar Cells. *International Journal of Renewable Energy Research*, **8**(4): doi: https://doi.org/10.20508/ijrer.v8i4.8579.g7526

Kowsar, A, Debnath, S. C., Haque, N., Islam, M. S., & Alam, F. 2022. Design of a 100 MW solar power plant on wetland in Bangladesh. *AIP Conference Proceedings*, **2681**(1): 20-72. https://doi.org/10.1063/5.0114976

Kurtz, S., Myers, D., McMahon, W. E., Geisz, J and Steiner, M. 2008. A comparison of theoretical efficiencies of multi-junction concentrator solar cells. *Progress in Photovoltaics: Research and Applications*, **16**(6): 537–546. https://-doi.org/10.1002/pip.830

Leite, MS., Woo, R. L., Munday, J. N., Hong, W. D., Mesropian, S., Law, D. C., & Atwater, H. A. 2013. Towards an optimized all lattice-matched InAlAs/InGaAsP/InGaAs multijunction solar cell with efficiency> 50%. *Applied Physics Letters*, **102**(3): 33901, https://doi.org/10.1063/1.4758300

Markvart, T. 2022. Shockley: Queisser detailed balance limit after 60 years. *Wiley Interdisciplinary Reviews: Energy and Environment* **11**(4): e430. https://doi.org/10.1002/WENE.430

Patel, P., Aiken, D., Boca, A., Cho, B., Chumney, D., Clevenger, M. B., Cornfeld, A., Fatemi, N., Lin, Y and Mccarty, J. 2012. Experimental results from performance improvement and radiation hardening of inverted metamorphic multijunction solar cells. *IEEE Journal of Photovoltaics*, **2**(3): 377–381. DOI: 10.1109/PVSC.2011.6186176

Rahaman, M. A., Hossain, M. I., Kamal, A., Sharif, M. N., Mursheduzzaman, & Chowdhury, A. M. 2021. Climate-Induced Displacement and Human Migration Landscape in Bangladesh. *Handbook of Climate Change Management*, 1865–1882. https://doi.org/10.1007/978-3-030-57281-5_255

Rahaman, M., Kowsar, A., Haque, N., & Azam, S. 2020. Photovoltaic energy in Bangladesh: Recent scenario, techno-economic evaluation, potential and challenges. *Journal of the Indian Chemical Society*. http://indianchemicalsociety.com/portal/uploads/journal/OB-16-2020.pdf

Shah, A., Torres, P., Tscharner, R., Wyrsch, N and Keppner, H. 1999. Photovoltaic technology: The case for thin-film solar cells. In *Science* (Vol. 285, Issue 5428, pp. 692–698. American Association for the Advancement of Science. https://-doi.org/10.1126/science.285.5428.692

Ushasree, P. M and Bora, B. 2019. *Chapter 1. Silicon Solar Cells,* pp. 1–55. Royal Society of Chemistry. https://-doi.org/10.1039/9781788013512-00001

Würfel, P and Würfel, U. 2016. *Physics of solar cells: from basic principles to advanced concepts*. John Wiley & Sons. ISBN: 978-3-527-41309-6

Yamaguchi, M., & Luque, A. 1999. High efficiency and high concentration in photovoltaics. *IEEE Transactions on Electron Devices*, **46**(10): 2139–2144, DOI: 10.1109/16.792009

Zou, C., Ma, F., Pan, S., Lin, M., Zhang, G., Xiong, B., Wang, Y., Liang, Y., & Yang, Z. 2022. Earth energy evolution, human development and carbon neutral strategy. *Petroleum Exploration and Development* **49**(2): 468–488. https://-doi.org/10.1016/S1876-3804(22)60040-5