INTERNATIONAL JOURNAL OF RENEWABLE ENERGY RESEARCH
Abu Kowsar et al., Vol.10, No.3, September, 2020

A Novel Simulator of Multijunction Solar Cells — MSCS-1D

Abu Kowsar*‡, Syed Nazmus Sakib**, Masum Billah***, Sujoy Dey***, Khaledun Nahar Babi****, Ali Newaz Bahar*****,******, Syed Farid Uddin Farhad****

*Institute of Fuel Research and Development, Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka-1205, Bangladesh

**Department of Electronics and Telecommunication Engineering, Daffodil International University, Dhaka-1207, Bangladesh.

***Department of Software Engineering, Daffodil International University, Dhaka-1207, Bangladesh.

****BCSIR Laboratories, Dhaka, Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka-1205, Bangladesh.

*****Department of Electrical and Computer Engineering University of Saskatchewan, SK, Canada.

******Department of ICT, Mawlana Bhashani Science and Technology University, Tangail - 1902, Bangladesh.

(apukowsar@gmail.com, nazmus.ete@diu.edu.bd, masum.swe.ndc@gmail.com, kumersujoy@gmail.com, khaledunnahar@gmail.com, bahar.ict@mbstu.ac.bd, sf1878@my.bristol.ac.uk)

‡ Corresponding Author; Abu Kowsar, IFRD, Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhanmondi, Dhaka-1205, Tel: +88 01722281618, apukowsar@gmail.com

Received: 07.07.2020 Accepted:24.08.2020

Abstract- In this work, a novel numerical analysis tool named one-dimensional multijunction solar cell simulator (MSCS-1D) has been reported. This numerical tool provides an easy platform to verify whether the intended work on a multijunction solar cell can be simulated as per expectations. A modified spectral p-n junction model has been used to develop this simulator. The congenial dialog box and graphical user interface (GUI) facilitate rapid data entry and visualization of the simulated results. To ascertain the performance of MSCS-1D, the simulated results from this tool were compared with MATLAB simulated results and found in good agreement. The newly developed simulator could provide the user with a smooth and fast-run operating procedure compared to the complex MATLAB programming as well as other solar cell simulators available in the literature.

Keywords- Device modeling; multijunction solar cell; interface development; simulator

1. Introduction

Solar cell simulation software or simulators are used to design and performance analyses of any kind of photovoltaic (PV) devices for better understanding their operation as well as further optimization prior to mass-scale production. There are various kinds of PVs [1, 2], and the PV community utilizes a number of simulators for assessing as well as improving device performance and design by employing numerical analyses. Among them, SCAPS [3], AFORS-HET [4], ASA [5], SETFOS [6], PC1D [7] are used to simulate the performance of a specific single-junction solar cell. On the other hand, COMSOL, Silvaco, Solcore, and AMPS are used to simulate the performance of different types of solar cells [8-11]. For example, AMPS is used for c-Si, a-Si:H, CIGS solar cell [10]. This class of simulators can also be used to simulate the performance of other optoelectronic devices, including light-emitting diodes (LEDs) and photodiodes [8, 9, 11]. All these simulation tools have been developed based on a specific theoretical model, such as the classic semiconductor drift-diffusion model [12]. A primitive version of the most simulators was only able to limited tasks [29, 30], and they have been improvised over the time for multipurpose usage, for example, Silvaco [9]. The most popular one-dimensional simulation tool: analysis of microelectronic and photonic structure (AMPS) has been used for single-junction solar cells simulation, originally developed by Professor Stephen Fonash et al. of Pennsylvania State University using Fortran programming language back in 1997 [10]. This simulator can perform the simulation work for amorphous silicon solar cells (a-Si:H), polycrystalline solar cells (pc-Si) and copper indium gallium selenide (CIGS) solar cells. The data entry in AMPS is seemingly cumbersome and time consuming as it needs to put a large number of parameters and layers. To allow the quick data entry and faster visualization of the simulation results, Yiming Liu et al. [13] reported an updated version of the AMPS simulator named wxAMPS in 2012. In fact, they replaced the original Fortran programmed source code of AMPS by C++ language and developed a cross-platform C++ library and wxWidgets to create a new graphical user interface (GUI). Further, this group revised the basic algorithm and incorporated the intraband tunneling and trap-assisted tunneling model in the wxAMPS analysis tool. These AMPS and wxAMPS simulation tools were developed by employing physics and semiconductor formulas of single-junction solar cells and they can efficiently simulate the performance of the device under investigation. Recently, a new version of wxAMPS (version 3) has been reported based on nonlocal band-to-band (B2B) tunneling model having multijunction solar cell simulating features [14]. Another popular simulation tool SILVACO ATLAS was developed in 2005 based on the transport of carriers through a two-dimensional grid by Sherif Michael et al. [15] in naval postgraduate school. This tool is used to predict the electrical characteristics of single-junction as well as multi-junction solar cells. Apart from them, commercially available technology computer-aided design (TCAD) tool was developed based on the B2B tunneling model and it has also been used to electrical/optical modeling of tandem solar cells [16]. Though most of the simulators stated above primarily have been developed for single-junction solar cells, however, TCAD and wxAMPS possesses additional features for simulating the multijunction solar cells (MJSC). To the best of our knowledge, there is no simulation tool in the photovoltaic literature specifically developed for multijunction solar cells using a dedicated theoretical model of MJSC. To bridge this literature gap, an easy accessing multijunction solar cell simulator has been developed based on a modified spectral p-n junction model for MJSCs [17], where JavaScript, Bootstrap, PHP and PHP: Security were used. The invocation of the later programming languages allows the simulator to run faster, more responsive and secured compared to C/C++ or Fortran based-simulators reported in the literature**.** To this end, a database-oriented website was created where the web version of the simulator has been uploaded for users to numerically analyze multijunction solar cells and to give feedback for further improvements. A runnable version of MSCS-1D can be found at https://mscs-bcsir.com/index.php

2. Multijunction solar cell model

The multijunction solar cell is considered as the state-of-the-art highest efficient solar cell for pushing its efficiency beyond the Shockley–Queisser efficiency limit. In MJSC, sub-cells or sub-layers are connected in either series or parallel, and each sub-cell is able to absorb different parts of solar insolation depending on the bandgaps of materials involved [15]. For MJSCs simulation, the MSCS-1D simulator has been developed on the basis of a recently modified version of the spectral p-n junction model [17, 18]. According to this modified model, all the sub-cells with approximately the same lattice constants are stacked in series for attaining current-matching conditions and optical transparency. This current matching condition ensures the same charge current to flow through all sub-cells. The tunneling junction in between the two sub-cells (such as in between p-type layer (p++) of top cell and n-type (n++) of the middle cell) is considered as an ideal ohmic contact to minimize the voltage drop at the tunneling junction [14, 17]. According to the physics of solar cells by Peter Würfel [19], for a given current, the voltages of different layers are determined from the individual cells and then added to give the overall voltage of any MJSC. The bottom cell with the smaller short-circuit current density determines the total current density. According to the modified model, the short-circuit current density (J_{sc}) has been determined from the ASTM G173-03 reference spectra [20], where the top cell thickness is taken as an adjustable parameter with other layers. The reverse saturation current density (Jo), has been calculated for each cell as the sum of the currents for the n-type and p-type layers. The open circuit voltage (V_{oc}), voltage (V_m) and current density (J_m) at the maximum power point, fill-factor (FF) and efficiency (η) have been calculated by using standard solar cell equations. In our MSCS-1D simulator, the numerical analyses have been performed using the standard equations for calculating the electrical characteristics of MJSCs. During the development of this simulator, above mentioned standard solar cell equations of the modified spectral p-n junction model have been indigenously programmed in JavaScript scripting language.

3. Graphical user interface (GUI) development

As mentioned above, a modified spectral p-n junction model has been invoked in developing this MSCS-1D simulator. For solving the standard semiconductor equations of this modified numerical model, JavaScript scripting language has been used. The utilization of JavaScript makes the numerical tool very fast in comparison to other programming languages such as C/C++, Fortran, etc. The GUI of this simulator was formed by designing front end user interface using popular tag-based technology HTML-5 (hypertext markup language) and CSS-3 (cascading style sheets, level 3). These two technologies are found to be very useful for creating the GUI in terms of facilitating the user for easy modification when urgent change is required to generate the desired outcome. Besides, this simulation software is very much device responsive. Bootstrap framework (HTML, CSS, and JavaScript) has been used for creating this fast responsive interface. In fact, this quick responsive feature makes this simulation tool suitable to run in any type of device such as computers, notebooks, tablets pc, and smartphones. For generating graphs, a JavaScript-based application program interface (API) library known as chart.js is used. Another popular API named html2canvas.js is used for quick downloading and converting the simulation graphs into a PNG image format file. Moreover, an in-house JavaScript API and window.print() API has been used to export the dataset in excel and PDF format, respectively. Besides, this web-based simulation tool could also be used as an offline desktop application. For desktop installation and security, 'Inno Setup' and 'PHP Desktop' application software have been used for creating installation files and executable files. For doing this, the webroot folder has been converted to an executable file by 'PHP Desktop v 57 with

PHP 7.1.3'. Then 'Inno Setup 5.6.1' software has been used to make an installation file.

4. Features

In the MSCS-1D simulator, the data entry option is relatively congenial compared to any other conventional solar cell simulators reported. For data entry, it requires to select the suitable sub-cell material. When one sub-cell is selected, it automatically takes the necessary optoelectronic parameters from the pre-loaded library built-in the simulator. This current version simulator is capable of simulating the performance parameters from two- to five-junction solar cells. To simulate a completely new sub-cell or new configured multijunction cell not available in MSCS-1D built-in library, one needs to enter the values of required optoelectronic parameters manually. The intended simulation then could be performed similarly as for predefined cells. More specifically, it is capable of simulating the short-circuit current density (Jsc), open-circuit voltage (Voc), and the current-voltage (J-V) characteristics curve of every sub-cell or junction of the MJSC to be investigated. It is also useful to perform very fast simulation of the overall multijunction solar cell's short-circuit current density (Jsc), reverse saturation current density (Jo), open-circuit voltage (Voc), voltage (V_m), and current density (J_m) maximum power point, fill-factor (FF), efficiencies (η) and the current-voltage (J-V) curve. Along with the normal atmospheric condition (1 sun condition), this simulator is also capable of simulating the cell performance for concentrating sun conditions (up to 1000 sun). It is possible to generate the sun concentration versus cell efficiency graph by this simulator, and in this way, one can easily estimate the concentrator cell efficiency up to 1000 sun illumination conditions. A very fast generating and downloading feature is introduced in this simulator. Graphs are generated within a fraction of a second, although graphs are created from more than thousands of datasets. Additionally, this proposed simulator is capable of exporting the dataset as an excel file or pdf file for further data processing and analyzing purposes. As a demonstration, herein, some current-voltage excel dataset has been used for generating the J-V characteristics curves using OriginPro:8.5 data analysis software.

5. Simulation and Discussion

The MSCS-1D tool can easily and effectively perform the simulation work for III-V multijunction solar cells with lattice match conditions. Other kinds of solar cells can also be simulated by this numerical tool provided that those cells satisfy the spectral p-n junction model. The simulation procedure can start by clicking the violet-colored SIMULATE icon on the homepage of this tool, and then it will ask the user to select the desire numbered multijunction solar cell. For example, if the user selects a three-junction solar cell, the blank dialog box shown in figure 1(a) will open. Then it again asks the user to select one sub-layer. After the selection of any semiconducting material as a sub-cell (for example, $GaInP_2$ as a top cell in a three-junction cell), this entire dialog box will be filled by a list of built-in optoelectronics parameters except the irradiance (I). The irradiance tab is left blank for the user to put the desired value as the value of irradiance is varied with different atmospheric conditions [21, 22]. In the case of $GaInP_2$, the irradiance value of 1415.28 $Wm^{-2}nm^{-1}$ has been manually put for air mass (AM) 1.5G under one sun condition from ASTM reference spectra for the corresponding wavelength 654.28 nm [20]. Then, the user can simulate the short-circuit current density and open-circuit voltage of the top cell ($GainP_2$), and there is an option to see the J_{sc} versus V_{oc} characteristics response for this sub-cell as well.

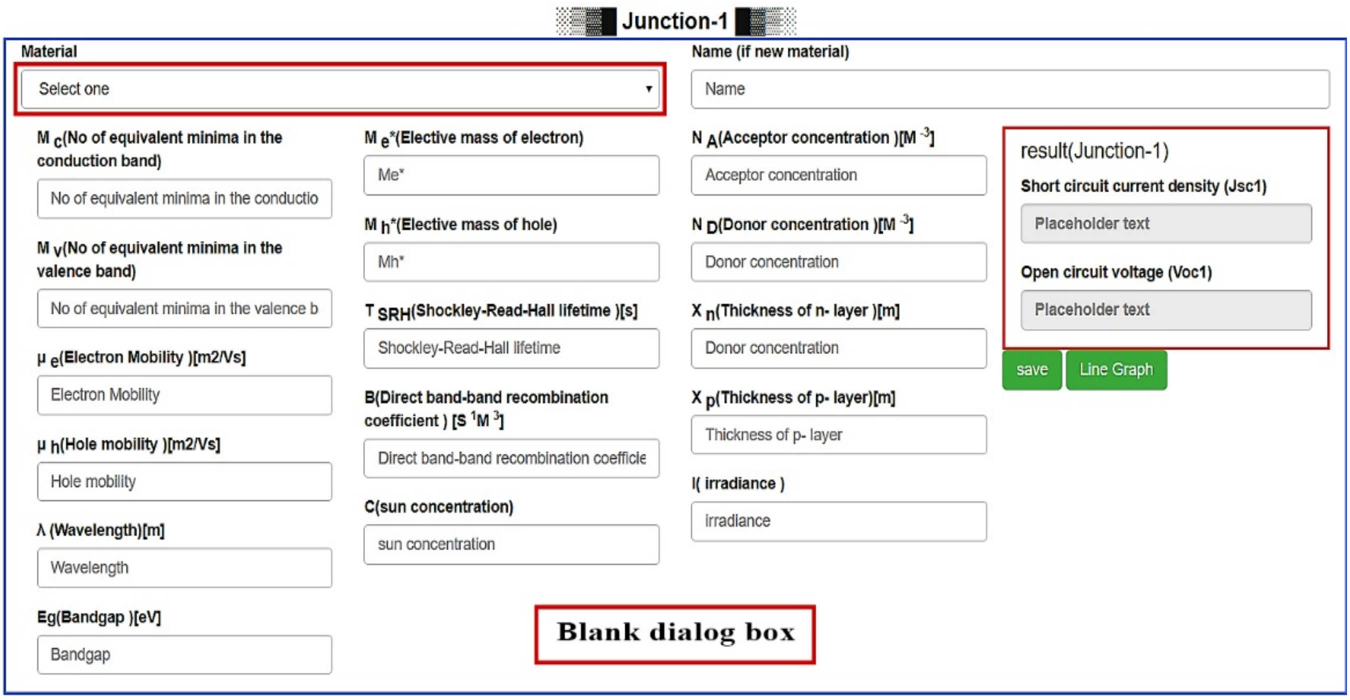

Figure-1(a): Blank dialog box of MSCS-1D simulator. The user is asked to 'select one' predefined sub-cell.

Figure-1(b): Filled dialog box of MSCS-1D simulator after the selection of the $GaInP_2$ subcell.

It is worth mentioning here that during the development of this simulator; this paper initially defined the values of five frequently used parameters such as the electronic charge (e), Plank's constant (h), light velocity (c), Boltzmann constant (k) and temperature (T) into our indigenously written JavaScript coding. However, when users select a specific sub-cell into the blank dialog box, the corresponding values of equivalent minima in the conduction band (M_c) and valance band (M_v), mobility of electron (μ_e) and hole (μ_h), wavelength (λ), bandgap (Eg), effective mass of electrons (m_e^*) and holes (m_h^*), Shockley-Read-Hall lifetime (τ_{SRH}), direct band-band recombination coefficient (B), acceptor concentration (N_A) and the donor concentration (N_D), and the thickness of p-layer (X_h) and n-layer (X_p) have been automatically populated from the built-in JavaScript library as shown in figure 1(b). Other required parameters of the modified spectral p-n junction model such as the diffusion constant of the electron (D_e) and hole (D_h), minority carrier lifetime of electron (τ_e) and hole (τ_h), intrinsic carrier concentration (n_i), surface recombination velocity of electron (S_e) and hole (S_h) of every selected sub-cell have been internally computed using JavaScript coding.

In this study, the performance evaluation has been performed based on the well-known $GaInP_2$/GaAs/Ge solar cell and emerging III-V Bismide multijunction solar cells [23-25]. Here, the default optoelectronic parameters have been used from refs. [23, 24, 26, 27]. The simulated results of short-circuit current densities and open-circuit voltages of initially defined seven sub-cells of the previously reported MJSCs [17, 24] are summarized in Table 1.

Table 1. Simulated results for different sub-cells of III-V multijunction solar cells generated by MSCS-1D.

Sub-layer	Bandgap, Eg (eV)	Short-circuit current, Jsc (mA/cm^2)	Open circuit voltage, Voc (V)
$GaInP_2$	1.90	74.48989	1.4359
GaAs	1.42	65.1982	1.0415
$GaAs_{.96}Bi_{.04}$	1.09	18.6099	0.675
$GaAs_{.95}Bi_{.05}$	1.00	17.748	0.584
$GaAs_{.94}Bi_{.06}$	0.92	15.621	0.496
$GaAs_{.92}Bi_{.08}$	0.704	16.397	0.276
Ge	0.67	16.2775	0.121

It is noticed that the higher bandgap material generates higher short-circuit current density and open-circuit voltage. For a specific cell configuration such as $GaInP_2$/GaAs/Ge, top cell $GaInP_2$ generates 74.48989 mA/cm^2 short-circuit current density and 1.4359 V open-circuit voltage, middle cell GaAs generates 65.1982 mA/cm^2 short-circuit current density and 1.0415 V open-circuit voltage and bottom cell Ge generates 16.2775 mA/cm^2 short-circuit current and 0.121 V open-circuit voltage. According to Peter Würfel [19] and current matching condition [24], the bottom cell with the smaller short-circuit current density 16.2775 mA/cm^2 determines the total current density of this cell. For the 16.2775 mA/cm^2 short-circuit current density, the voltages of different layers are calculated from the individual cells, and finally, adding all to generate the overall voltage of 2.599 V for $GaInP_2$/GaAs/Ge multijunction solar cells. The following Table 2 presents the MSCS: 1D simulated result for different types of multijunction solar cells.

Table 2. MSCS-1D **s**imulated results of five different configured multijunction solar cells.

Solar Cell	Short-circuit current density, Jsc (mA/cm^2)	Open-circuit voltage, Voc (V)	Max. current density, Jm (mA/cm^2)	Max. Voltage, Vm (V)	Efficiency (%)
$GaInP_2$/ $GaAs_{.96}Bi_{.04}$	18.609	2.106	18.369	1.992	36.6
$GaInP_2$/GaAs/Ge	16.278	2.599	16.109	2.480	40.2
$GaInP_2$/GaAs/$GaAs_{.94}Bi_{.06}$	15.621	2.973	15.480	2.851	44.1
$GaInP_2$/GaAs/$GaAs_{.95}Bi_{.05}$/ $GaAs_{.92}Bi_{.08}$	16.397	3.337	16.266	3.21	52.2
$GaInP_2$/GaAs/$GaAs_{.96}Bi_{.04}$/ $GaAs_{.92}Bi_{.08}$/Ge	15.621	3.765	15.511	3.637	56.4

The short-circuit current densities, open-circuit voltages, voltage, and current at the maximum power point, fill factors, efficiencies, etc. are considered as a performance evaluation matrix. The MATLAB has been considered as a cross-validation tool, and the identical multijunction solar cell was examined under the same atmospheric condition reported in [23, 24]. The proposed tool provides an identical result at the same atmospheric condition (AM1.5G).

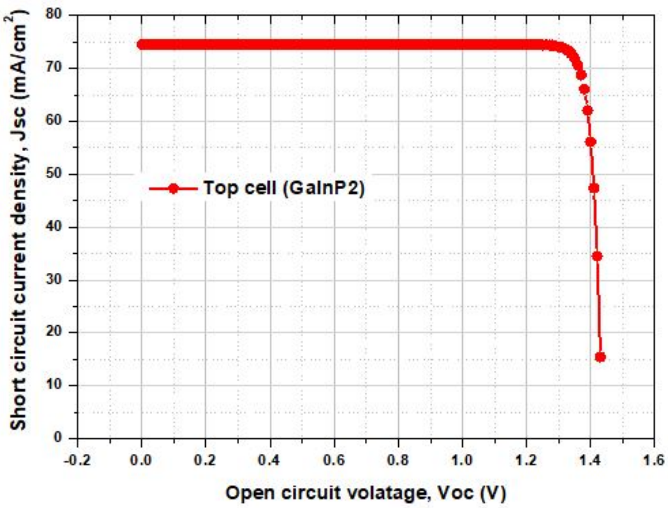

Figure 2(a). Jsc vs. Voc characteristics response of $GaInP_2$ sub-cell.

The MSCS-1D tool also possesses a feature to generate the current-voltage curves, i.e., J_{sc} vs. V_{oc} for different sub-cells as well as overall multijunction solar cells. For example, Figure 2 presents three J_{sc}-V_{oc} characteristics curves for the three sub-cells of $GaInP_2$/GaAs/Ge multijunction solar cells, and Figure 3 shows the overall cell current-voltage responses for the same MJSC. It is seen that there is also an agreement between the curves generated from our tool with the reported results [14, 28].

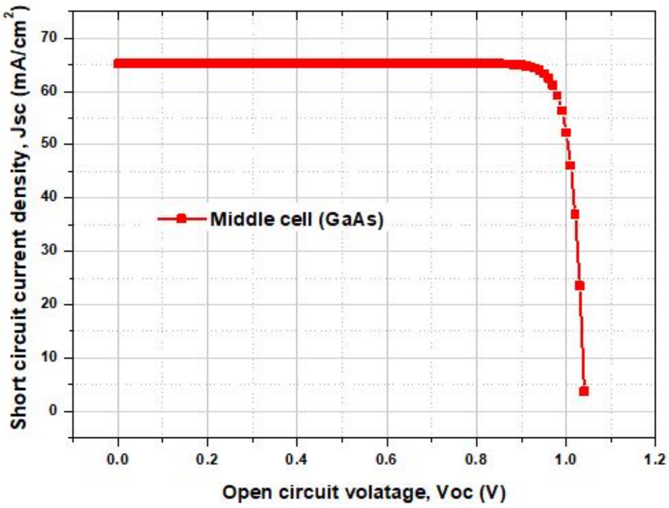

Figure 2(b). Jsc vs. Voc characteristics response of GaAs sub-cell.

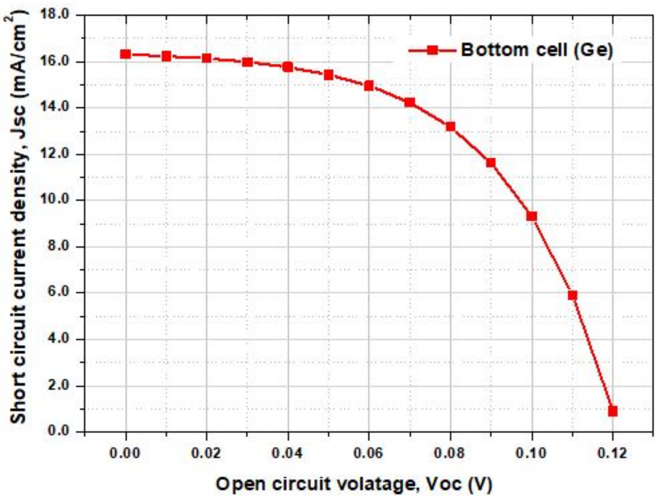

Figure 2(c). Jsc vs. Voc characteristics response of Ge sub-cell.

Figure 2. The current-voltage response of $GaInP_2$/GaAs/Ge multijunction solar cell is shown in figure 2, where Jsc vs. Voc response for subcell $GaInP_2$ is in Fig. 2(a), GaAs is in Fig. 2(b), Ge is in Fig. 2(c).

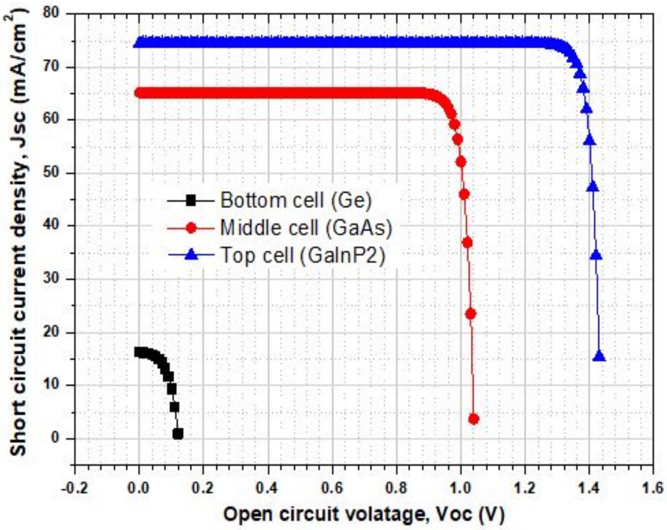

Figure 3. The combined current-voltage responses of $GaInP_2$/GaAs/Ge multijunction solar cells.

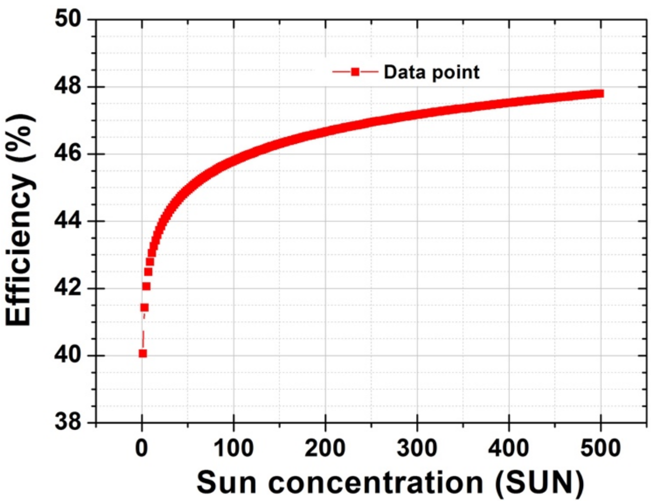

Figure 4. Sun concentration vs. efficiency responses of $GaInP_2$/GaAs/Ge multijunction solar cell.

The MSCS-1D provides users to investigate the effect of concentrated sunlight on the multijunction solar cell up to 500 suns. Figure 4 presents sun concentration vs. efficiency responses of $GaInP_2$/GaAs/Ge solar. In this figure, it is seen that the efficiency is increased quickly up to 100 suns, and then it is going to a constant value due to its material properties. This curve also shows good harmony with the reported curves [24].

Therefore, the present MSCS-1D simulator's results have been compared with those of the MATLAB as there is no simulation tool for high-efficiency MJSCs. This comparison helps the reader to understand how the JavaScript program makes this simulator faster. For simulating, we considered the following environment as operating system: Windows 10, processor: core i5 Intel, RAM: 8GB DDR3. From the comparison Table 3, it is seen that JavaScript is approximately 70 times faster than that of MATLAB [29].

Table 3. Simulations run-time checking for three-junction solar cell.

Attempt	Execution Time	
	MATLAB R 2018a	MSCS-1D (Browser: chrome)
1^{st}	70.14 seconds	0.89 second
2^{nd}	71.31 seconds	1.03 second
3^{rd}	69.95 seconds	0.98 second
Average Execution time	70.47 seconds	0.97 second

6. Conclusion

A novel and robust multijunction solar cell simulator named MSCS-1D simulator has been developed for PV researchers who lacks expertise in MATLAB or other similar programming languages or do not want to use any programming based compilers. The user-friendly interface facilitates a convenient framework to simulate a list of performance parameters such as short-circuit current densities, open-circuit voltages, reverse saturation current, current and voltages at the maximum power point, fill factors, efficiencies of multijunction solar cells. As a proof-of-concept, this numerical tool was used to estimate the efficiency of 40.2% for well-established $GaInP_2$/GaAs/Ge multijunction solar cells, and 36.6%, 44.1%, 52.2% and 56.4% efficiencies for two-, three-, four-, and five-layer emerging III-V Bismide based MJSCs respectively. The MSCS-1D facilitates a freeware simulation tool for the PV community to carry out theoretical studies and to support the experimental optimization for achieving state-of-the-art highest efficiency tandem solar cells.

Acknowledgment

Authors of this paper would like to acknowledge Mr. Sazzatul Yakin, Software Engineer of SoftCare IT for his technical supports. This work was financially supported by Ministry of Science and Technology, People's Republic of Bangladesh through the Special Allocation Project (Grant no.: 39.00.0000.09.02.90.18-19/09, Serial No. 458, Group order no: ID: 57; Date: 14.01.2019) and Bangladesh Council of Scientific and Industrial Research (BCSIR) R&D Scope (Ref. no: 39.02.0000.011.14.111.2019/228; Serial No. 41; Date: 06.11.2019).

References

[1] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, and X. Hao, Solar cell efficiency tables (version 56), Progress in Photovoltaics: Research and Applications, vol. 28, pp. 629-638, 2020.

[2] A. Kowsar, S. F. U. Farhad, M. Rahaman, M. S. Islam, A. Y. Imam, S. C. Debnath, M. Sultana, M. A. Hoque, A. Sharmin, Z. H. Mahmood, Progress in major thin-film solar cells: Growth technologies, layer materials and efficiencies, International Journal of Renewable Energy Research (IJRER), vol. 9, pp. 579-597, 2019.

[3] M. Burgelman, P. Nollet, and S. Degrave, Modelling polycrystalline semiconductor solar cells, Thin Solid Films, vol. 361, pp. 527-532, 2000.

[4] R. Varache, C. Leendertz, M. Gueunier-Farret, J. Haschke, D. Muñoz, and L. Korte, Investigation of selective junctions using a newly developed tunnel current model for solar cell applications, Solar Energy Materials and Solar Cells, vol. 141, pp. 14-23, 2015.

[5] B. Pieters, J. Krc, and M. Zeman, Advanced numerical simulation tool for solar cells-ASA5, IEEE 4th World Conference on Photovoltaic Energy Conference, 2006, pp. 1513-1516.

[6] B. Ruhstaller, T. Flatz, D. Rezzonico, M. Moos, N. Reinke, E. Huber, R. Hauseemanm, B. Perucco, Comprehensive simulation of light-emitting and light-harvesting organic devices, Organic Light Emitting Materials and Devices XII, 2008, p. 70510J.

[7] D. A. Clugston and P. A. Basore, PC1D version 5: 32-bit solar cell modeling on personal computers, Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference, pp. 207-2101997.

[8] S. Mahmoudinezhad, S. A. Atouei, P. Cotfas, D. Cotfas, L. A. Rosendahl, and A. Rezania, Experimental and numerical study on the transient behavior of multi-junction solar cell-thermoelectric generator hybrid system, Energy Conversion and Management, vol. 184, pp. 448-455, 2019.

[9] N. Boukortt, S. Patanè, and B. Hadri, Development of High-Efficiency PERC Solar Cells Using Atlas Silvaco, Silicon, vol. 11, pp. 145-152, 2019.

[10] H. Zhu, A. K. Kalkan, J. Hou, and S. J. Fonash, Applications of AMPS-1D for solar cell simulation, AIP Conference Proceedings, 1999, pp. 309-314.

[11] D. Alonso-Álvarez, T. Wilson, P. Pearce, M. Führer, D. Farrell, and N. Ekins-Daukes, Solcore: a multi-scale, Python-based library for modelling solar cells and semiconductor materials, Journal of Computational Electronics, vol. 17, pp. 1099-1123, 2018.

[12] S. Selberherr, Analysis and simulation of semiconductor devices: Springer Science & Business Media, 2012.

[13] Y. Liu, Y. Sun, and A. Rockett, A new simulation software of solar cells—wxAMPS, Solar Energy Materials and Solar Cells, vol. 98, pp. 124-128, 2012.

[14] Y. Liu, M. Ahmadpour, J. Adam, J. Kjelstrup-Hansen, H.-G. Rubahn, and M. Madsen, Modeling multijunction solar cells by nonlocal tunneling and subcell analysis, IEEE Journal of Photovoltaics, pp. 1363-1369, 2018.

[15] S. Michael, A. Bates, and M. Green, Silvaco ATLAS as a solar cell modeling tool, Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, 2005., 2005, pp. 719-721.

[16] M. Hermle, G. Letay, S. Philipps, and A. W. Bett, Numerical simulation of tunnel diodes for multi-junction solar cells, Progress in Photovoltaics: Research and Applications, vol. 16, pp. 409-418, 2008.

[17] A. Kowsar and S. F. U. Farhad, High Efficiency Four Junction III-V Bismide Concentrator Solar Cell: Design, Theory, and Simulation, International Journal of Renewable Energy Research (IJRER), vol. 8, pp. 1762-1769, 2018.

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

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

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

[21] 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.

[22] C. Gueymard, D. Myers, and K. Emery, Proposed reference irradiance spectra for solar energy systems testing, Solar energy, vol. 73, pp. 443-467, 2002.

[23] 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, Electrical Information and Communication Technology (EICT), 2015 2nd International Conference on, 2015, pp. 528-532.

[24] A. Kowsar, S. F. U. Farhad and S. N. Sakib, 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 (IJRER), vol. 8, pp. 2218-2227, 2018.

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

[26] A. 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.

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

[28] P. P. Altermatt, Models for numerical device simulations of crystalline silicon solar cells—a review, Journal of computational electronics, vol. 10, p. 314, 2011.

[29] A. G. Alkholidi, H. Haman, Solar Energy Potentials in Southeastern European Countries: A Case Study, International Journal of Smart Grid - ijSmartGrid, Vol 3(2), 2019.

[30] M. M. Rafique, Design and Economic Evaluation of a Solar Household Electrification System, International Journal of Smart Grid - ijSmartGrid, Vol 2(2), 2018.