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Research Article

MATLAB User Interface for Simulation of Silicon Germanium Solar Cell

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Nuclear fusion reaction on the sun is the largest source of energy. In this paper, qualitative investigation of the numerical model of silicon germanium heterojunction solar cell is performed using MATLAB graphical user interface. The heterostructure is designed as $Si_{1-x}Ge_x$ for speculative determination of appropriate germanium mole fraction to get the maximized thin-film solar cell efficiency ($\acute{\eta}$). Other characteristics such as absorption coefficient (α), energy band gap ($E_{g_{SiGe}}$), reflectivity (r), open circuit voltage (V_{oc}), and generation rate ($G(\lambda, x)$) are also considered. This user interface will reduce the complexity of solving differential equation for the analysis of silicon germanium heterojunction cell.

1. Introduction

Due to the constant increase in pressure on the nonrenewable energy sources, renewable energy sources are gaining popularity. Solar cell is an efficient type of renewable energy source. As compared to Si, Ge has steeper absorption edge and generally optical absorption coefficient of Ge is higher than that of Si. Silicon junction is stacked on top of a germanium junction for the enhancement of efficiency from a single junction Si solar cell [1]. The SiGe absorption behavior results in current gain, but at same time energy band gap of SiGe decreases. Various analyses on thin-film SiGe solar cells are carried to improve the characteristics and efficiency [2].

Heterojunction solar cells have a great advantage of achieving high electrical voltage [3] because material with large band has low minority charge concentration which leads to minimum recombination at the interface. For selection of better solar cell, semiconductor should be chosen on the basis of spectrum absorption [4]. Semiconductors like silicon and germanium have indirect band gap as shown in Figure 1 and it is used as an absorber in solar cell [5]. If we introduce Ge content in SiGe alloy its indirect band gap decreases. The main function of any indirect band gap semiconductor is trapping light; this can be enhanced by optimum texturing. Indirect band gap semiconductor also has high recombination lifetime and large diffusion length [6, 7].

Section 2 features the user interface. Section 3 includes the work of software interface; the structure of SiGe solar cell is modelled in Section 4. Section 5 focuses on the properties of SiGe alloy. Simulation results are presented in Section 6 with the simulated data.

2. User Interface Features

The purpose of this user interface is to develop a general purpose solar device simulator that is functional and modular in nature to allow flexibility during programming and provide sufficient scope for future developments. In addition, the program's main goal is to provide a tool that can supplement solar cell modeling, device physics and to construct basic cell equations using MATLAB tools. MATLAB's capability and inherent nature of handling matrices and matrix operations make it an optimum software for numerical analysis algorithms. A device modeling program is developed using basic MATLAB tools necessary to understand the operation of the program. The program solution will be used to examine device parameters such as carrier statistics, device potential, and internal electric fields. The device solution is compared to the analytical approximations in order to further

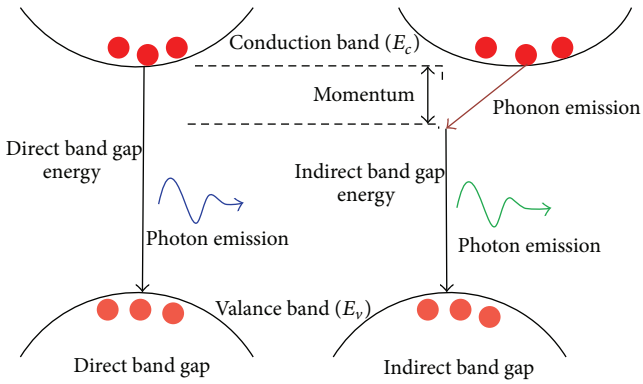

Figure 1: Direct and indirect band gap.

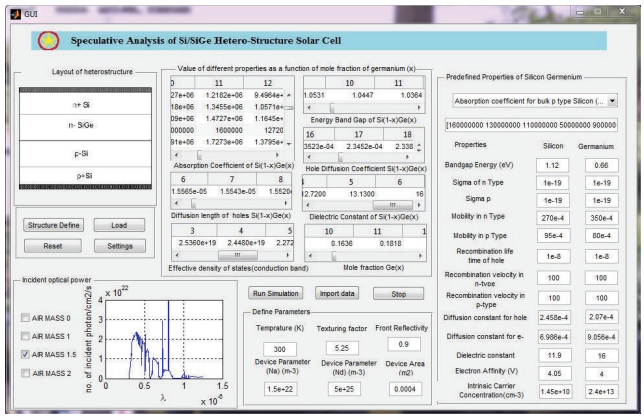

Figure 2: MATLAB GUI.

strengthen the understanding between theory and exact numerical solutions and how those solutions are obtained. In this software, silicon germanium solar cell analysis can be performed easily. Cell structure dimension is used with predefined parameters and electrical properties to solve the complex equation internally to provide best and instant result. Properties of silicon and germanium are prestored in GUI.

3. Graphical User Interface Working

Figure 2 shows the main window of this program. Initially, incident optical power is selected and different parameters like temperature, texturing factor, front reflectivity, device area, and device parameters are defined. In this program, properties of silicon and germanium are predefined, it can also be changed (increase digit after decimal), as per requirement for exact result, with the help of "Settings" button. Reset button is used to reconfigure the whole window except the predefined parameters. Button labeled as "Structure Define" is used for designing the layout of heterojunction Si/SiGe solar plate layer. Structure design is linked to new graphical user interface where it is loaded for further configuration settings of the model. Here, parameters like concentration, thickness of Si, SiGe, and lifetime of minority carrier (τ_p), along with mole fraction range, are required.

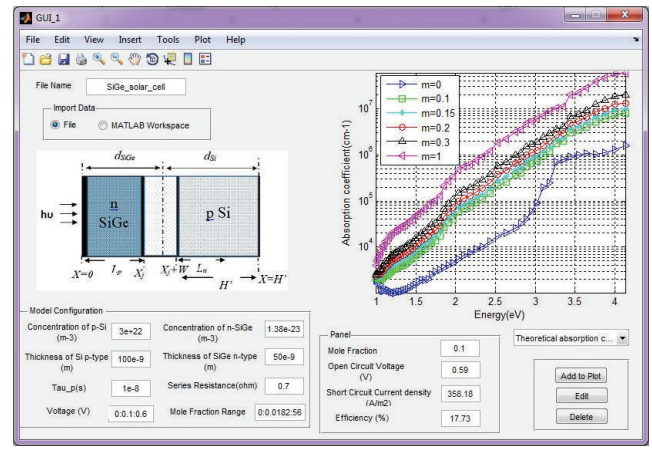

Figure 3: Structure define GUI.

For simulation purpose, enter the name of file and from the pop menu select the graph which is to be plotted. Simulate the result, which can be imported from MATLAB workspace or from a different folder. Figure 3 shows the simulation of absorption coefficient versus photon energy. It also simulates the value of the exact mole fraction, open circuit voltage, and short circuit current density at which efficiency is the maximum.

4. Cell Structure Properties

Any new method or other characterization methods with advanced numerical model can be simulated by changing the values and range of parameters. Developed numerical model [9]: thin layer of highly doped n-Si is constructed with a dimension of 5×10^{-9} m as a capping layer to increase luminescence efficiency. Alloy of silicon germanium is used in this layer and thickness d_{SiGe} is 50×10^{-9} m. Final layer is p-type doped silicon layer with thickness $d_{\mathrm{Si}} = 100 \times 10^{-9}$ m. The model is designed in such a way that numerical cell is represented in the form $\mathrm{Si}_{1-x}\mathrm{Ge}_x$, where x is the mole fraction of germanium which varies from $x = 0$, that is, pure silicon, until $x = 1$, that is, pure germanium, as shown in Figure 4. The surface recombination velocities (S_P) are 10^2 m/s at the front side and ∞ for the backside.

5. Properties of SiGe Alloy

The software calculates different properties corresponding to the mole fraction range (entered in structure define GUI_1). To compute different properties of alloy of silicon germanium, we need to analyze both semiconductors individually. To combine the effect of both semiconductors, Vegard's law is used, and this can be represented as [9]

$$P_{\mathrm{SiGe}} = P_{\mathrm{Si}}(1 - X) + P_{\mathrm{Ge}}(X), \quad (1)$$

where P_{SiGe} is the property of SiGe alloy, P_{Si} is the property of silicon, P_{Ge} is the property of germanium, and X is the mole fraction of Ge.

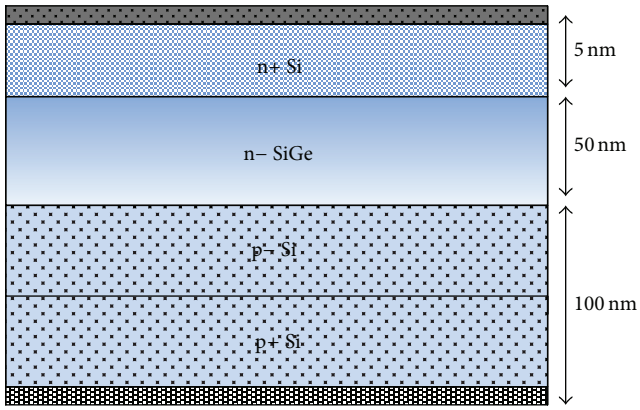

FIGURE 4: Schematic structure of Si/SiGe heterojunction solar cell.

Dielectric Constant (ε_r). The permittivity or relative dielectric constant of material is as follows:

$$\varepsilon_{r_{\mathrm{SiGe}}} = 11.9 + 4.1X. \tag{2}$$

Diffusion Length of Minority Holes (L_p). It is expressed as an average distance a carrier can move from the point of generation to recombination. Parameters play an important role in deciding the suitability of the material to be used as solar cell [10]

$$L_p = \sqrt{D_p \tau_p}, \tag{3}$$

where τ_p is the lifetime of minority holes in n-SiGe.

Energy Band Gap (E_g). It is the minimum amount of energy required for an electron to break free of its bound state. Due to the different thickness of Si and Ge alloys, the stacked layers are formed which relates to different energy thresholds, absorbing a different band of the solar spectrum over a wide range from silicon (1.12 eV) to germanium (0.66 eV). For type-I heterostructure, we use the relation

$$\Delta E_g = \Delta E_v + \Delta E_c. \tag{4}$$

Effective Density of States in Valence Band (N_v). Semiconductor's conductivity can be given by the relation

$$(\sigma) = q\left(\mu_n n + \mu_p p\right), \tag{5}$$

where μ_n is electron mobility, μ_p is hole mobility, n and p are electron and hole concentration, respectively. According to Maxwell-Boltzmann approximation, p depends on N_v (effective density of states in valence band).

Effective Density of States in Conduction Band (N_c). According to Maxwell-Boltzmann approximation, n depends on N_c (effective density of states in conduction band)

$$n_{i_{\mathrm{SiGe}}}^2 = N_{c_{\mathrm{SiGe}}} N_{v_{\mathrm{SiGe}}} e^{[-E_g/KT]}, \tag{6}$$

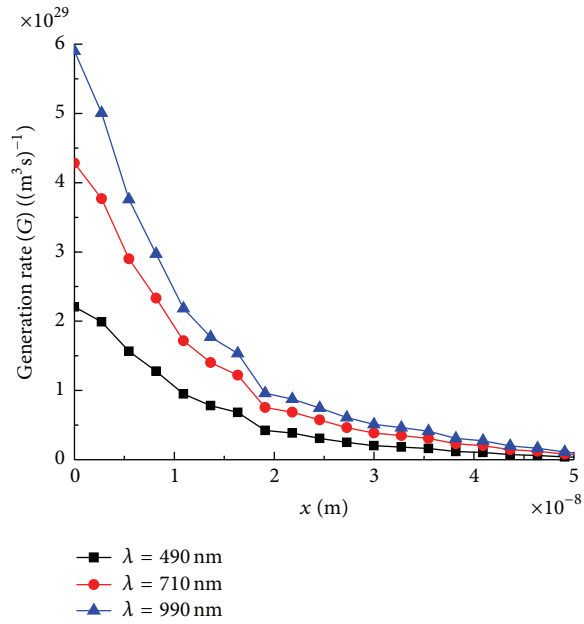

FIGURE 5: Generation rate at different wavelength.

where $n_{i_{\mathrm{SiGe}}}$ is the intrinsic carrier concentration, E_g is the energy band gap, and x is the Ge mole fraction [11]. The $n_{i_{\mathrm{SiGe}}}$, $N_{v_{\mathrm{SiGe}}}$, and $N_{c_{\mathrm{SiGe}}}$ values for different x values in $Si_{1-x}Ge_x$ heterolayers are in [9].

6. Simulation Result and Discussion

The absorption coefficients for n type Si and Ge and most of the parameters are taken from [12, 13]. The numerical value of the simulated properties of the alloy of SiGe is explained in Section 3. From Figure 2, it can be observed that important parameter at specified mole fraction is calculated and displayed in different tables as shown in Table 1. Results are simulated using this user interface and data is exported to OriginPro software for plotting. Some important results are shown.

6.1. Generation Rate. Absorption of photon in material leads to the number of electrons generated at each point. After reflection, the intensity of light to be absorbed depends on the material thickness and absorption as shown in the following equation:

$$G(\lambda, x) = \alpha(\lambda) F(\lambda) [1 - R(\lambda)] e^{-\alpha(\lambda)x}, \tag{7}$$

where $\alpha(\lambda)$ is the absorption coefficient of SiGe, $R(\lambda)$ is the reflectivity of silicon, $F(\lambda)$ is the number of incident photons per area per second, and x is the depth of layer of SiGe layer. Incident light is the combination of different wavelengths; therefore, generation rate corresponding to different wavelengths is shown in Figure 5.

To compute cumulative generation rate at different wavelengths, the sum of generation rate is calculated and used. From Figure 5, it is observed that, for the increase in wavelength, we get new shifted curve. Shifting is a cumulative

Table 1: Value of different properties as a function of mole fraction of germanium (x).

Properties of $Si_{1-x}Ge_x$	Si	$Si_{0.9}Ge_{0.1}$	$Si_{0.85}Ge_{0.15}$	$Si_{0.8}Ge_{0.2}$	$Si_{0.75}Ge_{0.25}$	$Si_{0.7}Ge_{0.3}$	Ge
ε_r	11.9	12.31	12.51	12.72	12.92	13.13	16
E_g (ev)	1.12	1.074	1.051	1.028	1.005	0.982	0.66
D_p (m^2/s)	2.458×10^{-4}	2.419×10^{-4}	2.399×10^{-4}	2.38×10^{-4}	2.361×10^{-4}	2.341×10^{-4}	2.07×10^{-4}
D_n (m^2/s)	6.986×10^{-4}	7.193×10^{-4}	7.3×10^{-4}	7.40×10^{-4}	7.50×10^{-4}	7.60×10^{-4}	9.056×10^{-4}
L_p (m)	1.567×10^{-5}	1.554×10^{-5}	1.549×10^{-5}	1.542×10^{-5}	1.536×10^{-4}	1.529×10^{-5}	1.438×10^{-5}
N_v (cm^{-3})	1.04×10^{19}	9.96×10^{18}	9.74×10^{18}	9.52×10^{18}	9.3×10^{18}	9.08×10^{18}	6×10^{18}
N_c (cm^{-3})	2.8×10^{19}	2.62×10^{19}	2.53×10^{19}	2.44×10^{19}	2.36×10^{19}	2.27×10^{19}	1.04×10^{19}
n_i (cm^{-3})	1.45×10^{10}	2.413×10^{12}	3.612×10^{12}	4.81×10^{12}	6.01×10^{12}	7.21×10^{12}	2.4×10^{13}

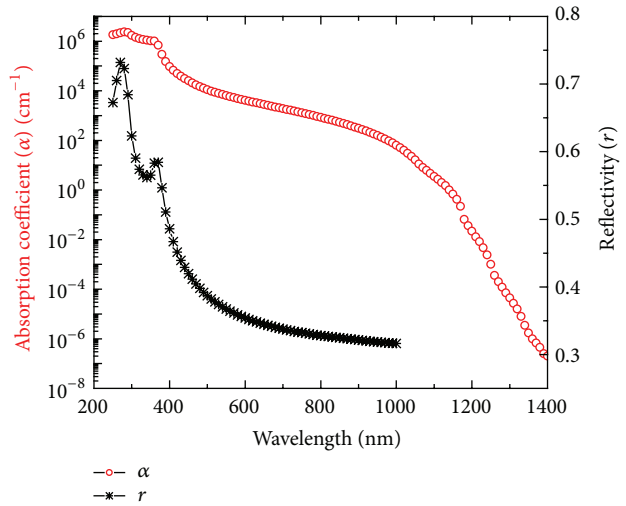

Figure 6: Silicon absorption coefficient and reflectivity with respect to wavelength.

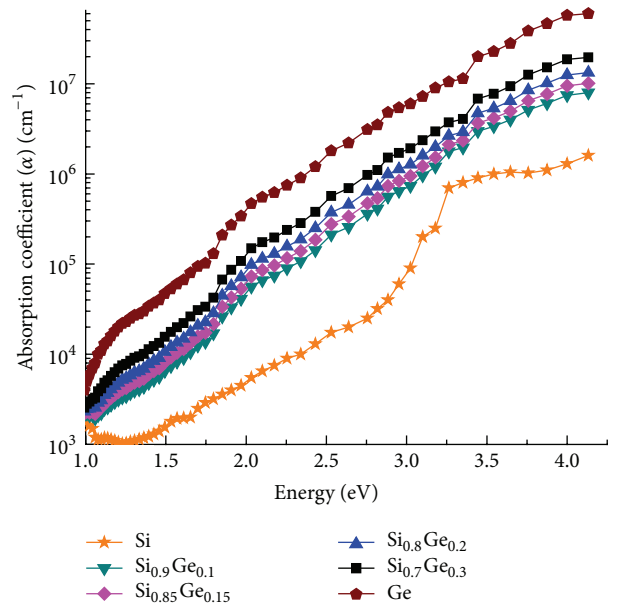

Figure 7: Theoretical absorption coefficient with photon energy of $Si_{1-x}Ge_x$.

effect of parameter such as absorption coefficients, reflectivity, and number of incident photons. When wavelength is increased, it leads to a decrease in both absorption coefficients and fraction of photon reflected as shown in Figure 6. Including all these factors along with the number of photons generated, the net effect increases the generation rate.

6.2. Absorption Coefficient versus Photon Energy of $Si_{1-x}Ge_x$. Absorption coefficient is a major parameter to decide at what material depth the light of particular wavelength can penetrate before it is absorbed. This coefficient depends on the material and the wavelength. In a semiconductor, having larger material absorption coefficient, the photons get more rapidly absorbed as well as the results in electron excitation in the conduction band. Therefore, selection of material for better solar cell is done with speculative analysis of the different characteristics of solar cell, and absorption coefficient is one of it. Therefore, the curve of absorption coefficient as a function of germanium mole fraction is plotted in Figure 7. Incident optical power under AM 1.5 is used for the simulation of $\alpha_{Si_{1-x}Ge_x}$. From Figure 7, it is observed that the absorption coefficient of Si is lower than Ge. Therefore, for photovoltaic material, crystalline Ge is better than crystalline Si because the optical absorption of germanium has a wider spectral overlap with the solar irradiance spectrum (Ge and Si cover 300 to 1600 nm and 300 to 1060 nm wavelength range, resp.) [1].

6.3. Current Density of $Si_{1-x}Ge_x$. Software compiles and produces current voltage characteristics curve with the help of predefined parameters, user defined parameters, constants, and silicon germanium properties, as shown in Figure 8. For the calculation of the total generated photocurrent, the program calculates the conduction current density due to holes and diffusion current density due to electrons and drift current density with the help of the equation in [9]. Current density at different Ge mole fraction is plotted as a function of voltage. It can be observed that when mole fraction is "0.3," the current density is the least, while if we take the value of the current density at Ge(x) = 0.25, it is increased. This behavior keeps on continuing, but certainly at mole fraction "0.15," the current density becomes the maximum. Therefore, on the basis of the theoretical observation, mole fraction between "0.1" and "0.15" for different characteristics is analyzed.

Table 2: Parameters obtained from simulator.

Illumination spectrum	R	Mole fraction	S_P (m/s)	τ_p (s)	N_A (m^{-3})	N_D (m^{-3})	V_{oc} (V)	J_{sc} (A/m^2)	Efficiency (%)
AM 1.5	0.9	0 (Si)	100	10^{-8}	1.5×10^{22}	5×10^{25}	0.68	78.94	4.67
AM 1.5	0.9	0.1 ($Si_{0.9}Ge_{0.1}$)	100	10^{-8}	1.5×10^{22}	5×10^{25}	0.59	358.18	17.73
AM 1.5	0.9	0.15 ($Si_{0.85}Ge_{0.15}$)	100	10^{-8}	1.5×10^{22}	5×10^{25}	0.56	382.5	17.47

Table 3: Comparison of efficiency of different model at the same mole fraction.

Different model	Mole fraction	J_{sc} (A/m^2)	V_{oc} (V)	Efficiency (%)
The proposed model	0.1	358.18	0.59	17.73
Said et al. [8]	0.1	183	0.55	7.5

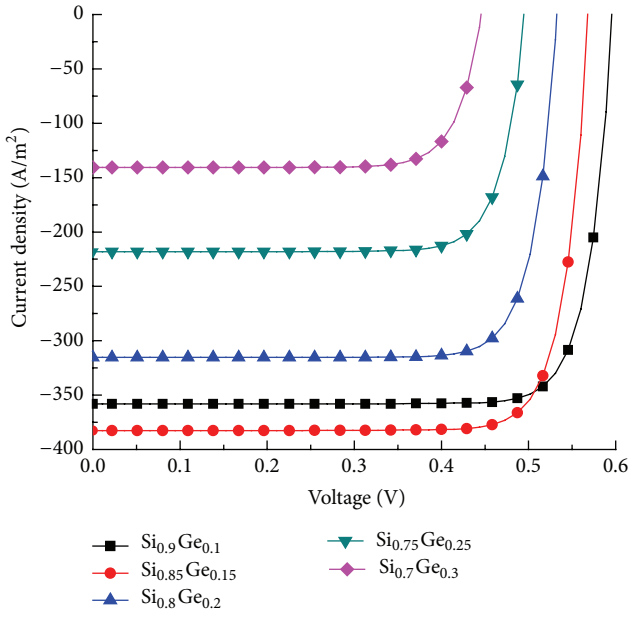

Figure 8: Current density voltage curve of $Si_{1-x}Ge_x$.

6.4. Open Circuit Voltage and Short Circuit Current of $Si_{1-x}Ge_x$. Open circuit voltage is the maximum voltage of solar plate and it occurs when the current is zero. It corresponds to the amount of forward biased solar cell due to the bias of cell junction with the light generated current [10]. It can be expressed as

$$V_{oc} = \frac{nkT}{q} \log_e \left(\frac{I_L}{I_s} + 1 \right), \quad (8)$$

where I_s is dark saturation current, I_L is light generated current, k is Boltzmann's constant, T is temperature in kelvin, n is ideality factor, and q is charge of an electron. From (8), it is concluded that open circuit voltage depends on $I_L = I_{sc}$ (short circuit current) and I_s, but actually the variation of I_{sc} is small. Therefore, it depends on the saturation current which may vary up to a significant margin. When mole fraction is increased, energy band gap of SiGe slopes down, which results in the increase in saturation current (I_s), as explained

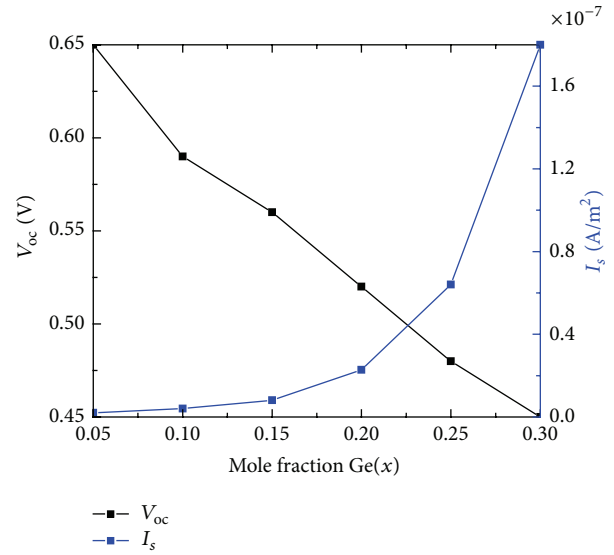

Figure 9: Open circuit voltage and saturation current as a function of mole fraction of Ge.

in [9] and as shown in Figure 9. Therefore, the combined effect of saturation current and short circuit current results in the decrease in the value of V_{oc} when mole fraction is increased. Value of V_{oc}, J_{sc} for better and efficient solar cell model is calculated and is displayed in the output panel: germanium mole fraction is "0.1," where open circuit voltage is "0.59 V" and short circuit current density is 358.18 A/m^2, producing the maximum efficiency of 17.73 (%). Efficiency was calculated assuming 1000 W/m^2 as the input power.

The maximum theoretical efficiency of a single p-n junction solar cell can be calculated by Shockley Queisser limits. With the proposed theoretical approach, if we simulate the efficiency of pure silicon, that is, at a mole fraction "0," the efficiency is less as compared to SiGe alloy, as shown in Table 2. This is because at higher band gap most of the solar photons are not able to convert into electrons that flow through the circuit [14]. Therefore, to reduce band gap and to enhance absorption, alloy of silicon and germanium is constructed. In Table 3, some present methods are compared with the proposed method.

7. Conclusion

This user interface can be used for speculative analysis of silicon germanium heterostructure solar cell. Here, modelling of different layer is done easily and it instantly switches

over to the calculation mode. If needed, arbitrary parameter variation could be done for simulation of different characteristics. This is very useful in deciding the perfect combination of germanium content and thickness of silicon germanium layer as per the requirement. SiGe alloy layer is a tunable absorber layer, suitable for construction of efficient and optimized solar cell. According to [9], time for extraction of data was long, but, for this user interface, the result computation time is less. This GUI can be used to optimize the following $Si_{1-x}Ge_x$ parameters: (a) properties variation with variable layer thickness; (b) effect on electrical and structural properties under variation of temperature. In future, the program can be enhanced for the simulation of different heterojunction solar cell. An efficiency of 17.73% was realized with the proposed technique and this heterojunction method will overcome the maximum practical Si efficiency of 26% in the future.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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