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Efficiency enhancement in SiGe thin film solar cell by a CNT grating structure

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In this paper, a new structure of SiGe thin film solar cell using a carbon nanotubes (CNT) grating layer is proposed. CNT grating layer is used which reduces the reflection loss from the surface and maximizing optical absorption in the active layer of the cell. In order to reduce the carrier recombination in the back contact, a GaAs back-surface field (BSF) layer was used. The simulation results show that the efficiency of the proposed structure is 29.32%. Furthermore, we were able to increase the efficiency to 31.3% by optimizing the structural parameters including the depth and number of grating periods.

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1. Introduction

Due to global warming and increasing energy demand, many scientists are doing research to improve the efficiency and reduce the cost of solar cell in order to commercialize these devices [1]. Among the types of solar cells, thin film cells have been of interest for many years due to the reduction of raw material consumption, ease of installation, and flexibility. The thickness of these layers varies from a few nanometers to tens of micrometers and is much thinner than the old technology and the first generation of crystalline silicon solar cells [2]. Most of the solar cells are designed to receive the visible spectrum, so for better absorption in the entire radiation spectrum of sunlight, we need materials with an energy gap smaller than 1.1 eV such as silicon germanium with an energy gap of 1.08 eV. SiGe has other advantages compared to silicon, which makes it more useful in solar cells. The higher number of free electrons of germanium compared to silicon, higher conductivity, adjustable absorption coefficient and energy gap, better physical characteristics and improved electrical properties of silicon have led to the use of SiGe in solar cells [3]. However, the addition of germanium to silicon reduces the band gap and hence increases the short circuit current and decreases the open circuit voltage of the cell. Therefore, it is necessary to use the optimal percentage of germanium in the SiGe material [4]. In recent years, the SiGe layer has also been used as a buffer layer between the layers of III-V groups and silicon in cascade cells due to its ability to adjust the bandgap. On the other hand, double-junction SiGe/GaAs cells are also of interest as the end layers of multi-junction cells due to the absorption of high wavelengths up to 1800 nm [5-7].

In addition to the type of material, various other factors affect the performance of the solar cell. The most important of these factors are the losses caused by the shadow of the upper metal contact and the electrical resistance on the way of the generated carriers to the upper contact. An effective way to overcome these two efficiency limiting factors is to use carbon nanotubes (CNT) in solar cell structures.

CNTs are suitable materials for using in solar cell devices due to their high mobility, high electrical conductivity and creation a low resistance path for the charge carriers, high transparency and ease of manufacturing processes. The use of CNTs in solar cells has been reported in many literatures as an active layer, a charge collector layer, an electrode, and a P layer [8-15]. Also, due to the high cost and complexities of manufacturing and the problems of making a good ohmic

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contact between III-V group with transparent conductive oxides, the CNTs are a substitute alternative for them [16-17].

The heterogeneous CNT networks have been shown to have very high electrical conductivity and transparency [18]. We recently proposed a SiGe thin film solar cell structure using the heterogeneous CNT networks layer as the charge collector [19]. Using this layer, we could extend the distance between the contact grid lines. Therefore, the shadowing effect of the upper metal contact as well as the electrical resistance in the path of the carriers is reduced and as a result the efficiency of the cell increases.

To increase the power conversion efficiency (PCE) in solar cells, a series of measures are taken to increase the absorption of sunlight in the absorber layer of the cell, which is called light management. These measures include methods to minimize reflection losses from the surface such as the using anti-reflection coatings, textured interfaces, and light trapping techniques. In solar cells whose absorber materials have a diffusion depth much greater than the thickness of the absorber layer, there is effective absorption only in a certain spectral range. For such materials, light trapping techniques are used to increase absorption by creating scattering in the grating structure on one or both sides of the cell. In fact, these techniques increase the absorption rate by increasing the average effective path length of photons in the absorbing layer of the cell [20-24]. Since the performance principles of such gratings are highly dependent on structural parameters such as the number, depth, duty cycle, and periodicity, analytical models have been presented to optimize the grating structure to maximize light trapping in solar cells [25].

In this paper, a new structure of SiGe thin film cell is proposed which reduces two other efficiency limiting factors including losses due to light reflection of cell surface and carrier recombination in back contact. In this structure, the cell efficiency is improved by using a CNT grating layer and a GaAs BSF layer. We will also maximize the efficiency of the proposed cell by optimizing structural parameters such as grating depth, width and period. The structure of the following paper is as follows: In the second part, the structure of SiGe solar cell with CNT grating layer is introduced. In the third part, the cell simulated model is given. In the fourth part, the obtained results are discussed and evaluated. In the fifth section, the conclusion is given.

2. The proposed cell structure with CNT grating layer

The schematic structure of the proposed SiGe(x=0.1) thin film solar cell with CNT grating layer and GaAS BSF layer is shown in Fig. 1. The gold top contact grid has a width of 50 μm and a thickness of 100 nm, which covers about 18% of the cell surface. This structure consists of a p-type GaAs layer with a thickness of 500 nm as a window layer, a p-type SiGe layer with a thickness of 400 nm as an emitter layer, an n-type SiGe layer with a thickness of 8 μm as a base layer, an n-type SiGe layer with a thickness of 10 μm as a substrate layer and a GaAs BSF layer with a thickness of 2 μm as the carrier recombination reducer in the back contact. In this structure, a semi-transparent CNT networks layer with a thickness of 100 nm is used as a charge collector. In this structure, the top metal electrode is replaced by a contact grid for reducing shadowing effect. Using a CNT charge collector layer increase the distance between metal grid lines and hence decrease the losses due to shadowing effect. On the other hand, the CNT layer with high conductivity could decrease the internal resistance that seen by the carriers. All these together could enhance the total performance and efficiency. One of the most important factors limiting efficiency is the light reflection from the cell surface. CNT grating layer is used to reduce the reflection from the cell surface on top of the charge collector layer, in the areas where there is no contact. The basic structural parameters of the grating are listed in Table 1.

The CNT layer used in this structure is a heterogeneous network of carbon nanotubes, which is made by dipping polyethylene terephthalate (PET) films in a solution containing carbon nanotubes (CNT ink). A heterogeneous CNTs network with 128Ω/□ was fabricated and reported by the Institute for Micro Structural Science of Canada [26]. This layer has high transparency, whose transmission spectrum is shown in Figure 2.

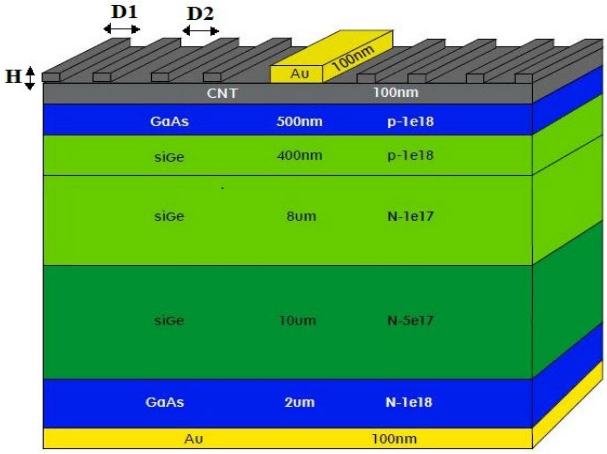

Fig. 1. The proposed cell structure with CNT grating layer.

Table 1. The basic structural parameters of the grating layer.

Parameters	Description	Value
H	Grating depth	10 nm
D_1	Ridges width	10 μm
D_2	Grooves width	10 μm
Λ	Period (D_1+D_2)	20 μm
H	Duty cycle	50%

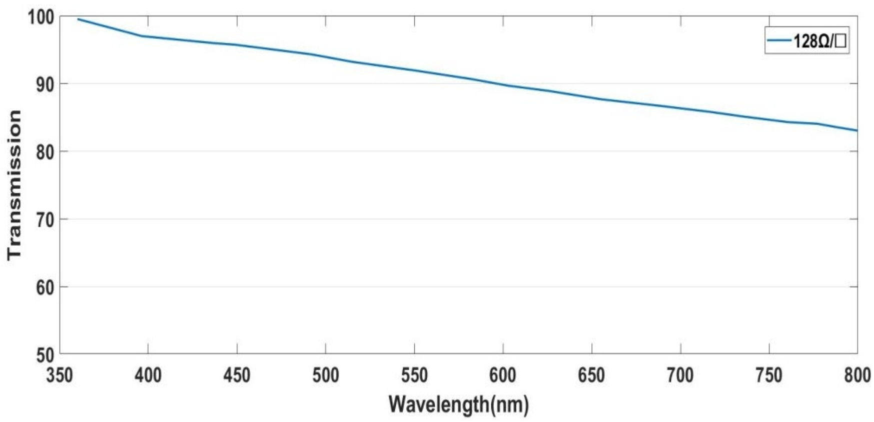

Fig. 2. Transmission spectrum of the CNT layer [18].

3. Method and theoretical model

The total current of the solar cell is obtained from the sum of the drift and diffusion currents. By irradiating light to the structure, the generated electron-hole pairs are separated by the electrostatic field inside in the depletion region of the structure and reach the electrodes, which create a drift current. On the other hand, the diffusion current is caused by the variation in the carrier concentration in the cell. We use the drift-diffusion model to describe the transport of charge carriers inside the device. This model includes drift-diffusion equations and continuity equations for electron and hole which are solved along with Poisson's equation. The drift-diffusion equations are given below:

$$J_p = J_p^{drift} + J_p^{diff} = -q\mu_p p\nabla\phi - qD_p\nabla p$$

$$J_n = J_n^{drift} + J_n^{diff} = -q\mu_n n\nabla\phi + qD_n\nabla n \tag{1}$$

where J_n and J_p are electron and hole current densities. μ_n and μ_p are the electron mobility and hole mobility, respectively. Φ is the electrostatic potential, and D_p and D_n represent the diffusion coefficient for holes and electrons, respectively. The continuity equations are as follows

$$\nabla.\mathrm{J}_n = \mathrm{q}(G_n - R_n) \tag{2}$$

$$-\nabla.\mathrm{J}_P = -\mathrm{q}(G_p - R_p) \tag{3}$$

where q is the elementary charge. G_n and G_p are the rates of electron and hole generation. R_n and R_p are the electron and hole recombination rates, respectively. Poisson's equation is given below:

$$-\nabla.\varepsilon\nabla\psi = \mathrm{q}\rho \tag{4}$$

where ε is the dielectric constant. By numerically solving the coupled equations (1) to (4), the I-V curve of the solar cell is obtained. Using the I-V characteristic, performance parameters such as: short circuit current (I_{sc}), open circuit voltage (V_{oc}), fill factor (FF), and efficiency (η) are obtained. The output current of solar cell (I) is calculated by following equation:

$$I = I_d - I_L = I_0\left[\exp\left(\frac{qV}{KT}\right) - 1\right] - I_L \tag{5}$$

where I_d is dark current and I_L denotes the current generated by light and I_0 is the reverse saturation current. The output voltage is calculated as $V=I\times R_L$. When the load is open ($I = 0$), the photo-generated current under open circuit is equal to the dark current. Therefore, the open circuit voltage can be obtained as follows.

$$V_{oc} = \frac{KT}{q} ln\left(\frac{I_L}{I_0} + 1\right) \tag{6}$$

The output power of solar cell is:

$$P = I \times V = \left(I_0\left\{e^{\left(qV/KT\right)} - 1\right\} - I_L\right) \times V \tag{7}$$

The voltage V_M is occurred at the maximum power, it can be calculated by derivative of equation (7) and then we have:

$$V_M = V_{OC} - \frac{KT}{q}\ln\left(1 + \frac{qV_M}{KT}\right)$$

$$I_M \cong I_0\left(1 - \frac{KT}{qV_M}\right) \tag{8}$$

The maximum power is then calculated as $P_M = I_M \times V_M$. Fill factor that indicates the ratio of area of rectangle $I_M \times V_M$ to area of rectangle $I_{SC} \times V_{OC}$ is defined as:

$$FF = \frac{I_M V_M}{I_{SC} V_{oc}} \tag{9}$$

Finally, the conversion efficiency of solar cell can be obtained as:

$$\eta = \frac{P_M}{P_{in}} = \frac{I_M V_M}{P_{in}} = \frac{FF \cdot I_{SC} V_{OC}}{P_{in}} \tag{10}$$

where P_{in} is the input light power density, which is considered to be 1000 Wm^{-2}. It is obvious from equation (10) that the solar cell efficiency is closely related to fill factor, short circuit current, and open circuit voltage. Therefore, these parameters are extracted to calculate the efficiency of the proposed cell structure.

4. Results and discussion

The light reflection spectrum of the cell surface calculated by the Finite-Difference Time-Domain (FDTD) method is shown in Fig. 3. Using the grating layer can reduce the losses caused by light reflection from the cell surface. As Fig. 3 shows, the spectrum of light reflection from the cell surface in the structure with the CNT grating layer is significantly reduced compared to the structure without the grating layer. Therefore, more photons enter the structure and this creates more electron-hole pairs in the structure and as a result improves cell performance and increases efficiency.

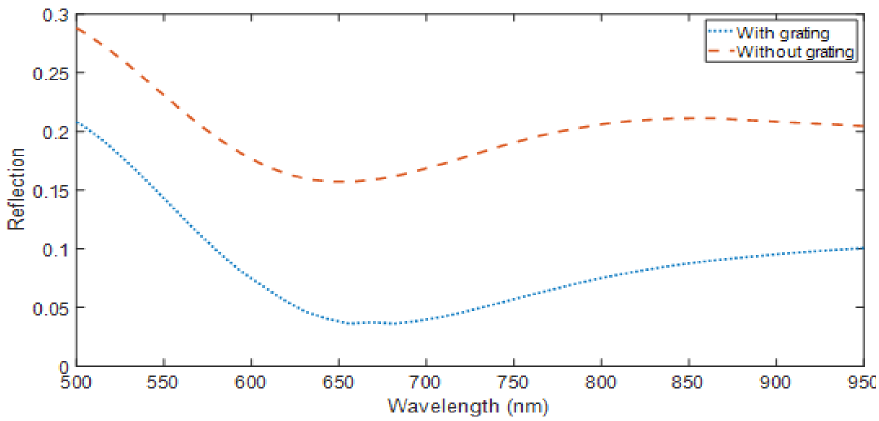

Fig.3. The spectrum of light reflection from the cell surface of structure with and without grating.

In order to evaluate the performance of the proposed solar cell, we simulate the structure and obtain the voltage-current characteristic, and then extract the performance parameters such as short circuit current, open circuit voltage, fill factor and efficiency. The parameters used in this simulation are listed in Table 2.

Table 2. Simulation parameters [4, 19].

Layer identifier	GaAs material	$Si_{(0.9)}Ge_{(0.1)}$ material
E_g (eV)	1.42	1.08
Affinity (eV)	4.07	4.045
Permittivity ε_r (Fcm^{-1})	13.1	12.15
μ_n (cm^2/Vs)	8000	1000
μ_p (cm^2/Vs)	400	500
Conduction band effective density of state N_C (cm^{-3})	4.7×10^{17}	2.62×10^{19}
Valence band effective density of state N_V (cm^{-3})	7×10^{18}	0.996×10^{19}

Figure 4 shows the current-voltage curve of the proposed structure in two cases of the presence and absence of the grating for comparison. As can be seen, the presence of gratings has increased both the short-circuit current and the open-circuit voltage. The presence of grating reduces light reflection from the cell surface and traps more light photons inside the structure and increases light absorption. Therefore, the generation of electron and hole pairs in the active region of the cell increases and this increases the cell current (I_L). It is clear from equation (6) that as the photo-generated current of the cell increases, the voltage of the open circuit of the cell also increases. Therefore, we will expect an improvement in cell performance and an increase in cell efficiency. Table 3 shows the performance parameters of the cell, including short circuit current, open circuit voltage, filling factor, maximum power and cell efficiency in two cases of with and without the grating.

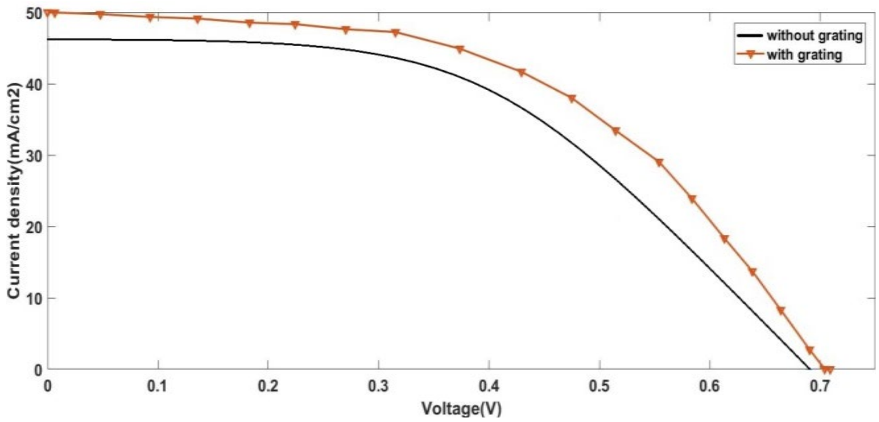

Fig. 4. I-V curve for comparison in two cases of with and without grating.

Table 3. Performance parameters comparison with and without grating.

Solar structure		$J_{sc}(A/cm^2)$	$V_{oc}(V)$	$P_{max}(W/cm^2)$	FF %	E_{ff} %
Structure without grating		0.046	0.69	0.025	84.11	28.2
Structure with grating		0.05	0.709	0.028	83.95	29.32

In addition, in the proposed structure a high doped GaAs layer is used as the back-surface field layer (BSF). The presence of energy offset of conduction and valance bands at the interface of SiGe and GaAs layers creates a barrier in front of the carriers and prevents recombination in the back contact. Reducing the recombination in the back contact, which is one of the important factors of losses in the solar cell, improves the performance and increases the efficiency of the proposed cell. Fig. 5 shows the energy band diagram of the proposed cell structure and the presence of energy offset at the interface of SiGe and GaAs layers.

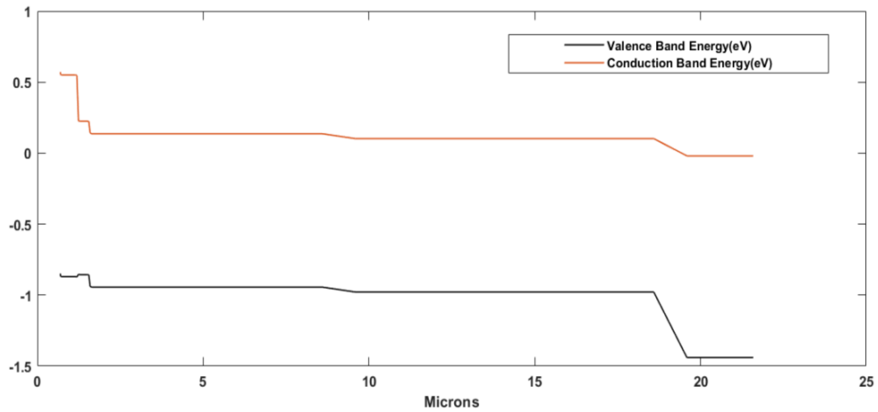

Fig. 5. Energy band diagram of proposed structure.

In order to better investigate the effect of the CNT grating layer and the GaAS BSF layer, we also calculate and evaluate the external quantum efficiency (EQE) parameter of the structure. The external quantum efficiency is equal to the ratio of the total carriers produced to the total photons irradiated to the solar cell. This parameter decreases due to various factors such as surface reflection losses, surface recombination and back contact recombination. In our proposed structure, this parameter has been tried to be improved by using a grating layer on the cell surface as a surface reflection reducer and a BSF layer as a back-contact recombination reducer.

Fig. 6 shows the external quantum efficiency curve in three cases: the initial structure without CNT and BSF layers, the modified structure with the application of CNT charge collector layer and BSF layer, and the complete proposed structure with CNT charge collector layer, BSF layer and CNT grating layer. As can be seen, the blue EQE curve shows the typical structure without CNT and BSF layers, which has a maximum quantum efficiency of about 60%. The red EQE curve shows the structure with CNT charge collector layer and BSF layer but without CNT grating, which has improved quantum efficiency compared to the initial structure, so that the maximum quantum efficiency is about 70%. In fact, this EQE increase compared to the initial structure is the effect of the presence of the CNT charge collector layer and the GaAs BSF layer. The green EQE curve shows the proposed complete structure with CNT charge collector layer, BSF layer and CNT grating layer, which has increased compared to the previous two structures and its maximum has reached about 80%. This increase is related to the effect of reducing surface reflection losses created by the grating layer.

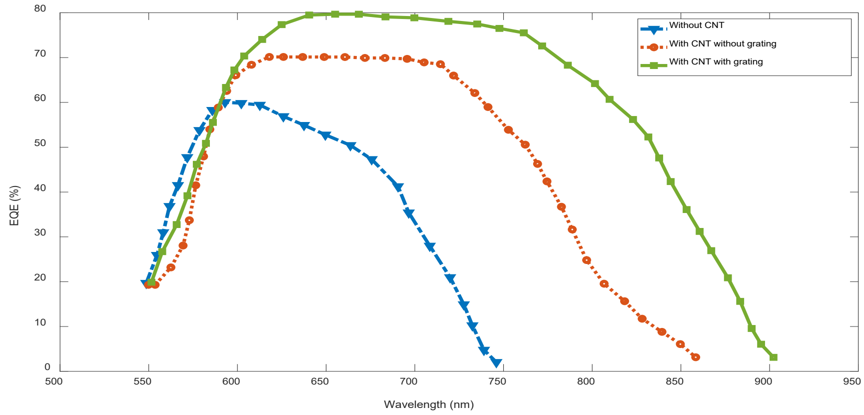

Fig. 6. Comparison of the EQE of solar cell for three structures.

Also, we investigate the effect of temperature changes on the performance of the proposed cell structure. Fig. 7 shows the I-V curve of the structure at temperatures of 273, 300 and 350 K. As can be seen, the short circuit current increased and the open circuit voltage decreased with increasing temperature. An increase in temperature causes the bandgap to narrow, resulting in more photons being absorbed by the structure, and this increases the short-circuit current. On the other hand, narrowing the bandgap increases the density of intrinsic carriers and this increases the reverse saturation current and thus decreases the open circuit voltage. Of course, the open circuit voltage drop rate is more than the short circuit current increase rate. Therefore, increasing the temperature in general reduces the efficiency of the cell.

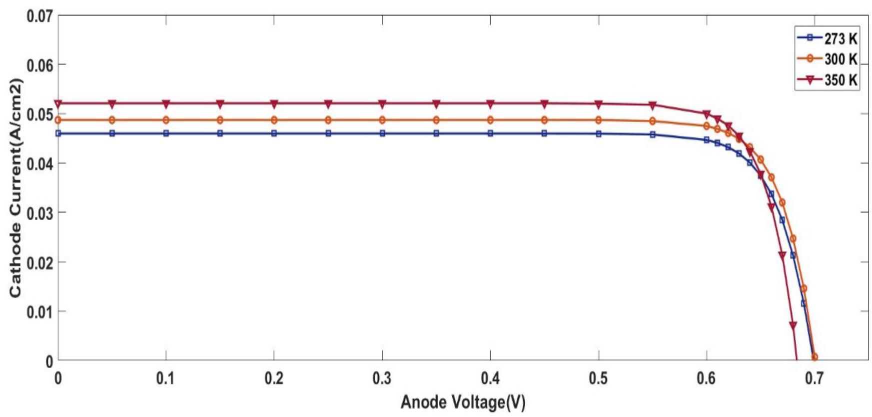

Fig. 7. Effect of temperature changes on the performance of the cell.

In order to increase the efficiency of the proposed cell, the structural parameters of the grating, including the number of periods and depth of the gratings, are optimized. Fig. 8 shows the EQE of the proposed cell for different values of the number of periods on each side of the upper contact. Fig. 9 shows the EQE of the cell for different grating depth values. It can be seen from Figures 8 and 9 that for the number of grating periods for each side of the upper contact of 6 and the grating depth of 13 nm, the EQE of the cell is maximized. By optimizing the number of grating periods, the maximum quantum efficiency reaches 84% and after optimizing the grating depth, the maximum quantum efficiency reaches 86%.

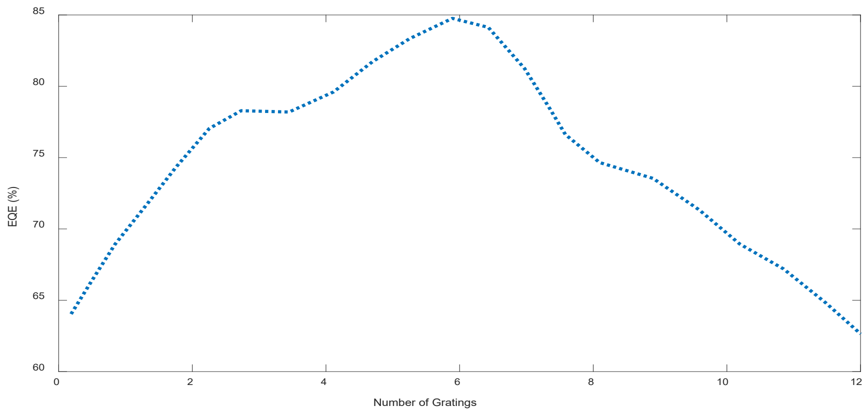

Fig. 8. The maximum EQE as a function of grating periods.

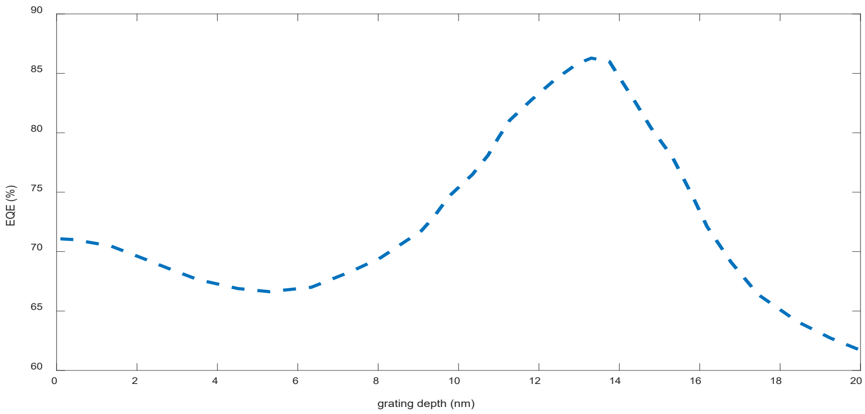

Fig. 9. The maximum EQE as a function of the grating depth.

The current-voltage curve of the cell before and after grating optimization is shown in Fig. 10. As can be observed, the optimization of the structural parameters of the grating, have increased the short circuit current and fill factor parameter of the cell. The efficiency of the proposed cell after optimizing the structural parameters of the grating is calculated to be about 31.3%.

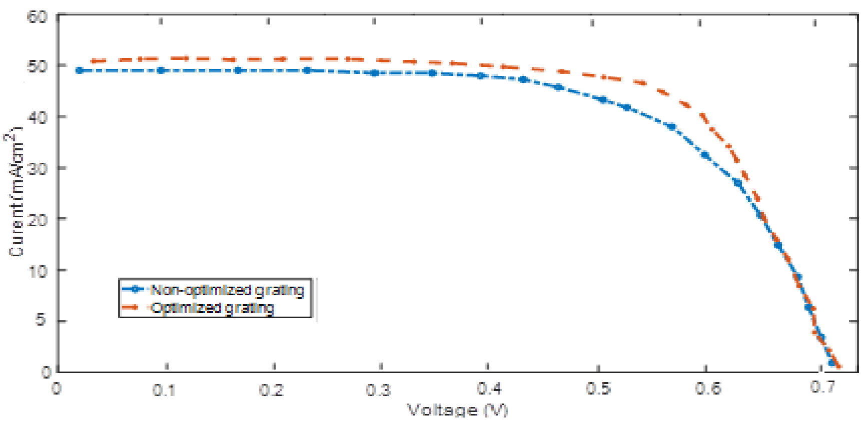

Fig. 10. Current-voltage curve of cell before and after optimization.

5. Conclusion

In this paper, a SiGe thin film solar cell structure using CNT grating layer has been proposed. In this structure, a CNT layer was used as a charge collector under the top metal contact grid to reduce the shadowing effect and a CNT grating layer was used to reduce the light reflection losses from the cell surface. Also, in order to reduce the recombination of carriers in the back contact, a GaAs BSF layer has been used in this structure. The simulation results show that the efficiency of the proposed structure is 29.32%, which is higher in comparison to conventional structures without CNT layer. In addition, by optimizing the structural parameters including the grating depth and number of grating periods, we were able to increase the efficiency of the proposed cell to 31.3%.

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