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A novel trapezoidal profile of optimized diffraction grating for light trapping in thin silicon solar cells

MAHYAR DEHDAST[1*], ALI BAHRAMI[2], SHAHRAM MOHAMMADNEJAD[1]

[1] Electrical and Electronics Engineering Department, Nanoptronics Research Center,
Iran University of Science and Technology, Tehran, Iran

[2] Department of Electrical Engineering, Sahand University of Technology, Tabriz, Iran

[*] Corresponding author: mahyardehdast@alumni.iust.ac.ir

In this paper, we propose a new design and comprehensive optimization process for improving the diffraction gratings used as the back reflector of silicon solar cells. For this process, the optimum refractive index and its corresponding available material which can be used as the grating material has been chosen as 1.57 and SiO_2, respectively. Also, all of geometric parameters which affect the performance of the grating, such as periodicity, height and depth of grating profiles have been studied and the appropriate values for each of them have been proposed. In order to optimize the profile of grating, a transition from triangular to rectangular structure has been considered and finally a specific trapezoidal profile has been chosen as the optimized grating back reflector which enhances the cell efficiency up to 6%. Simulation results show that the different grating profiles have the same duty cycle and therefore use the same amounts of materials.

Keywords: diffraction grating, light trapping, quantum efficiency, solar cell.

1. Introduction

Higher thickness of an active layer in silicon solar cells increases the carrier recombination, resistivity and manufacturing costs. Therefore, although decreasing the active layer of silicon solar cells decreases the absorption probability of incident photons, the recent cells move toward ultra-thin silicon solar cells (UTSSC) [1]. On the other hand, the effective absorption region of the photons will be reduced by degrading the thickness. Hence, there will be a requirement for the light trapping techniques in order to enhance the absorption probability by increasing the optical path length (OPL). The various light trapping methods which have been recently suggested are included in texturing [2, 3], plasmonics [4, 5], layered media [6–8], diffractions [9] and so on. Also the third-generation photovoltaics have been investigated in order to increase the total cell efficiency [10–12]. Among these methods, the periodic structures are commonly used due to greater control on geometric parameters of structure and higher effect on light trapping. Diffraction gratings are one of the periodic structures which result in an improvement in the absorption and cell efficiency with increasing the OPL of photons [13]. These structures can be used as the back reflector structure of solar cells, scatter the incident light in the different directions and enhance the quantum efficiency (QE) and therefore total efficiency of the cell. The effective parameters in the operation of diffraction gratings are included in the material and geometry of grating.

In this paper, we propose a new design of the diffraction grating back reflector and optimize different parameters in order to achieve the highest achievable light trapping. A grating structure has been designed and optimized in order to return the non-absorbed photons of a specified bandwidth into the silicon medium. The optimum refractive index and its corresponding available material which can be used as the grating material will be chosen. Also, all of geometric parameters which affect the performance of the grating, such as periodicity, height and depth of grating profiles have been studied and the appropriate values for each of them have been proposed, which results in an increase of 6% of cell's efficiency.

A brief theoretical background of diffraction gratings and the design parameters of the proposed structure will be presented in Section 2. In Section 3, different effective parameters of grating will be optimized. Finally, the effect of the optimized back reflector structure on the cell's electrical and optical characteristics will be discussed in Section 4.

2. Design

Diffraction grating is a periodic structure which scatters the incident light beam in different angles. The diffraction angles can be defined as [14]

$$\sin(\theta_m) = \frac{m\lambda}{nd} \tag{1}$$

where m, λ, n and d are diffraction order, incident wavelength, refractive index and period of grating, respectively. In periodic structures, the effective intensity of light inside the structure is increased by $4n^2$. Therefore, the optical absorption of the structure can be calculated as [15]

$$A = 1 - \frac{1}{1 + 4n^2 \alpha T_c} \tag{2}$$

where α and T_c are the absorption coefficient and thickness of the absorber layer, respectively. This effect results in the corresponding increment of quantum efficiency. Increasing the quantum efficiency (QE) enhances the short circuit current as follows [9]:

$$I_{sc} = \frac{q}{hc} \int_{\lambda_{min}}^{\lambda(E_g)} \lambda \, QE(\lambda) \, S(\lambda) \, d\lambda \tag{3}$$

where q, h, c and $S(\lambda)$ are elementary charge, Planck's constant, light speed and the solar spectrum, respectively. Therefore, an optimized light trapping structure can in-

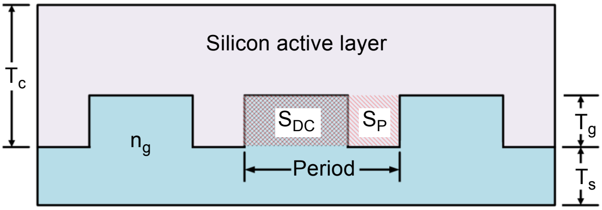

Fig. 1. Schematic structure of proposed grating.

troduce an extensive enhancement on the short circuit current and increase the total cell efficiency. The schematic structure of the grating back reflector is depicted in Fig. 1.

As can be seen in Fig. 1, the important parameters which can affect the performance of the grating structure are shown in Fig. 1. The duty cycle (DC) of grating can be calculated with dividing its area on the total area of period (P) equal to S_{DC}/S_P. The profile of grating can be enhanced with optimizing the refractive index, duty cycle and period of grating. For the first step, the most suitable material should be chosen.

Rigorous coupled wave analysis (RCWA) has been utilized in order to simulate the light profile in proposed periodic structures (diffraction grating) and verify the performance of the structure under the defined circumstances. This method provides an absorption spectrum of the whole structure to complete the modeling process of the solar cell. In the calculation of RCWA method, we assumed a two-dimensional structure which is periodic in the horizontal direction. However, we have considered just one period for simulation. In fact, the considered simulation region which is just one of the infinite periods is the worst case.

So, the efficiency of the silicon solar cell has been calculated for different refractive indices of grating. The effect of refractive index variations on the cell efficiency is shown in Fig. 2.

As can be seen in Fig. 2, the optimum refractive index of grating is achieved as 1.57. There are some available materials such as Al_2O_3 and SiO_2 with the refractive indices

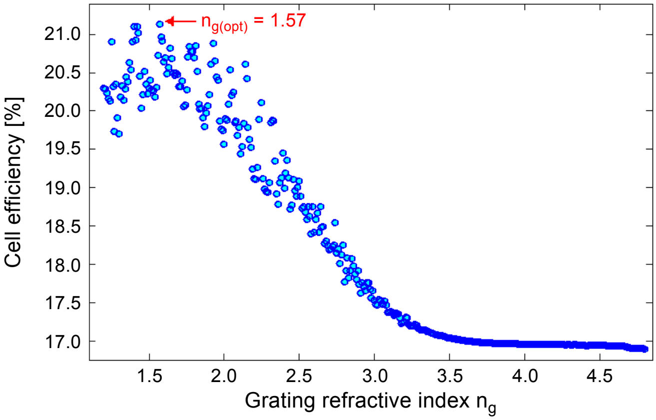

Fig. 2. The curve of cell efficiency *versus* grating refractive index.

near the optimum value. In this paper, the SiO_2 has been chosen as the most suitable material of the proposed grating-based back reflector. In next sections, the SiO_2 proposed structure will be optimized.

3. Optimization procedure

From Figure 1, with considering SiO_2 as the material used, the duty cycle and period of grating should be optimized. For a typical range of the period, the duty cycle of grating can be changed from zero to 100%. The effects of grating duty cycle, period, depth T_g and sub-thickness T_s variations on the cell efficiency are presented in Fig. 3.

Figure 3**a** shows the effect of the duty cycle and the period of grating on the efficiency of the silicon cell. The optimum combination of the period and duty cycle of grating has been obtained as point A with the values of 796 nm and 60%, respectively. With utilizing these values for the period and duty cycle of grating, the depth and sub -thickness of grating has been optimized and the results of simulation are depicted in

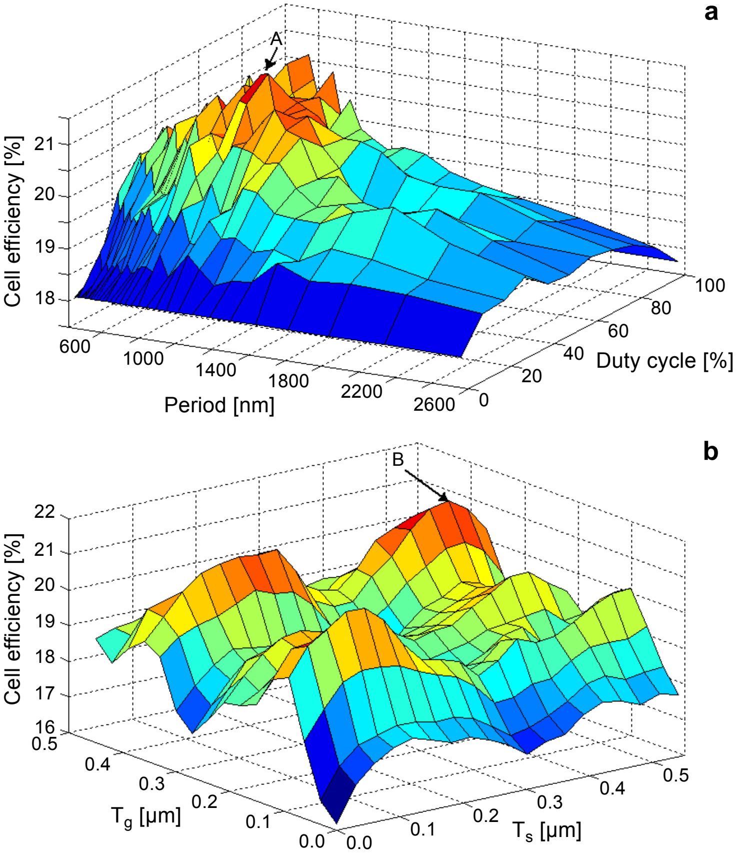

Fig. 3. The effects of grating geometry variation on the cell efficiency: variations of period and duty cycle (**a**), and variations of depth T_g and sub-thickness T_s (**b**).

Fig. 3**b**. The optimum values for depth and sub-thickness of grating which can be referred to point *B* are 360 and 480 nm, respectively.

The achieved values for different parameters of grating have been calculated for the conventional rectangular profile. This profile can be modified to a more optimized structure with increasing the W_b from Period × DC to Period and decreasing W_t from Period × DC to zero. Therefore, the profile of grating can be varied from a rectangular to triangular structure. The proposed structure of the grating back reflector is presented in Fig. 4.

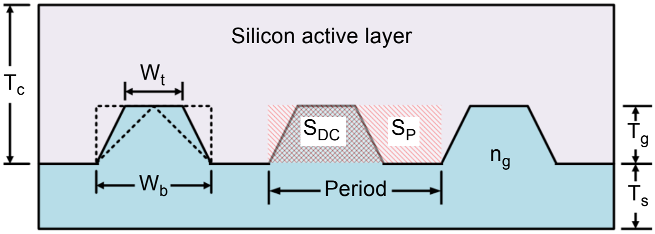

Fig. 4. Proposed profile of grating back reflector.

The duty cycle of grating which has been optimized to 60% presents the percentage of material used for a grating profile. Hence, it seems that the duty cycle (and therefore the amount of material used) should be constant for different grating profiles. The effect of changing W_t and W_b on the performance of the proposed structure has been simulated and shown in Fig. 5.

As can be seen in Fig. 5, the optimum combination of parameters W_t and W_b are obtained as 298 and 597 nm, respectively. It is obvious that the corresponding structure of grating will be a trapezoidal profile which can extremely enhance the performance of the solar cell. The new duty cycle corresponding to a trapezoidal profile is calculated

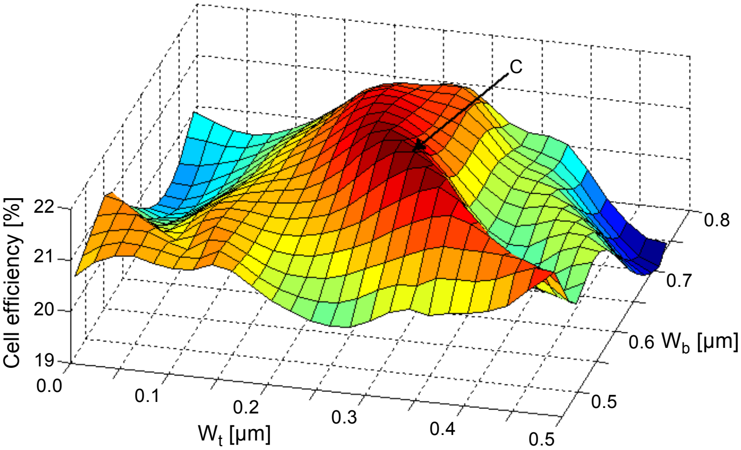

Fig. 5. The curve of cell efficiency *versus* W_t and W_b.

as 56%. Therefore, it can be concluded that different grating profiles present the similar duty cycle.

4. Discussion

After the optimization procedure, all of the grating physical parameters are chosen. These parameters which construct the configuration of the proposed back reflector are given in the Table. Besides the grating structure with utilizing SiO_2 as the available material, the proposed structure has been simulated and optimized for the ideal structure with the refractive index of 1.57. The optimum values for physical parameters which have been achieved for the ideal refractive index of 1.57 are also presented in the Table.

The trapezoidal grating structure has been utilized as the back reflector of silicon solar cell. The absorption spectrum and quantum efficiency of silicon solar cell without

Table. The obtained values of optimum grating structure.

Material	Duty cycle [%]	Period [nm]	T_g [nm]	T_s [nm]	W_t [nm]	W_b [nm]	Current density [mA/cm^2]	Cell efficiency [%]
$n_g = 1.57$	55	644	100	100	214	474	34	22.35
SiO_2	60	796	360	480	298	597	33.6	22.1

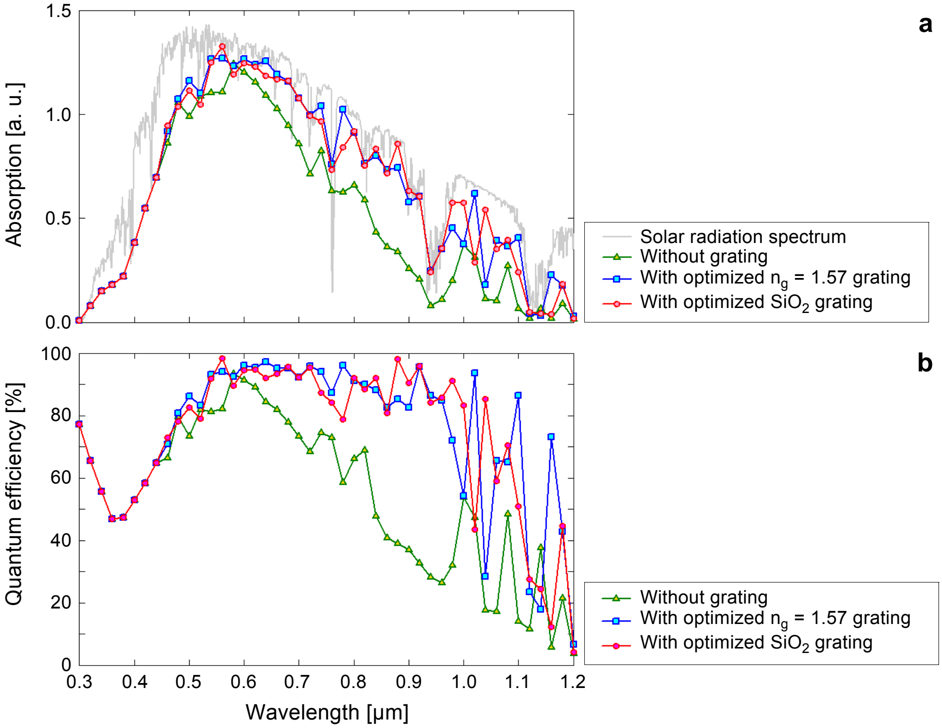

Fig. 6. The absorption spectrum (**a**), and quantum efficiency (**b**) of silicon solar cell.

and with optimized grating back reflector (ideal and SiO_2 grating structure) are shown in Fig. 6.

Figures 6**a** and 6**b** emphasize that the back reflector structure has the lowest impact on the device performance in lower wavelengths. Therefore, the optimized diffractive back reflectors remarkably affect the performance of silicon solar cell in the range of solar spectrum peak (650 nm). The design wavelength λ in our calculations has been assumed as 650 nm and we designed the grating structure for this wavelength. Also, it can be seen that the back reflector with utilizing SiO_2 shows almost the same behavior as the ideal refractive index. The current-voltage characteristics of silicon solar cell with optimized gratings can be seen in Fig. 7.

The comparison of current-voltage curves for silicon solar cell with and without utilizing optimized gratings show a current density enhancement of 9.4 mA/cm^2 for the best case. The simulation results about absorption and short circuit current shows a good coincidence with Eqs. (2) and (3). It should be noticed that the proposed structures are utilized as the back reflector of typical silicon solar cell with the cell thickness

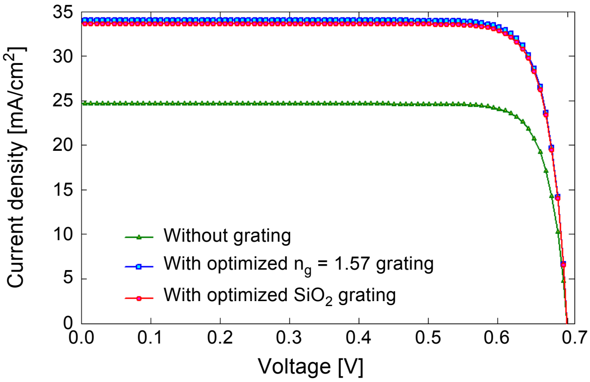

Fig. 7. The current-voltage curve of silicon solar cell with proposed optimized gratings.

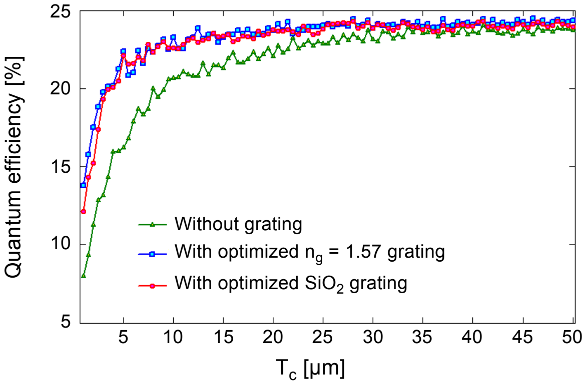

Fig. 8. The curve of cell efficiency *versus* the variations of cell thickness for two cases: with and without optimized gratings.

of 5 µm. The thickness of the absorber layer affects the device performance and changes the dependence of device performance on the back reflector structure. The curve of cell efficiency *versus* the thickness of the absorber layer is shown in Fig. 8. for two cases: with and without optimized gratings.

As can be understood from Fig. 8, the performance of solar cells with lower absorber layer thicknesses shows the higher enhancement for the case of utilizing the optimized reflector structure.

5. Conclusion

We proposed a new trapezoidal profile for the grating back reflector with optimized geometrical parameters in order to be used in thin silicon solar cells. For conventional binary grating, the optimum refractive index of 1.57 corresponds to the available material of SiO_2 which can be used as the grating material. Also, all of geometric parameters which affect the performance of the grating, such as periodicity, height and depth of grating profiles have been studied and the appropriate values for each of them have been proposed. In order to optimize the profile of grating, a transition from triangular to rectangular structure has been considered and finally a specific trapezoidal profile has been chosen as the optimized grating back reflector which enhances the cell efficiency up to 6%. The same duty cycle which has been achieved from the simulations of different grating profiles emphasizes that the amount of materials used for all of grating structures will be constant.

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