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EFFECT OF USING MIRRORS ON THE EFFICIENCY OF SILICON SOLAR CELL TEXTURED WITH TRIANGULAR GROOVES BY USING ZEMAX

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Abstract: Solar cell (photovoltaic cell)efficiency depends on the amount of sunlight falling on its surface and reflection within the cell. Different methods are used to improve solar cell efficiency. In this paper, we use triangular grooves on the upper surface of the silicon cell to reduce outside reflection on the surface of the cell and increase the internal reflection withinthe cell by putting mirrors on the four sides of the cell. We compare the performance of this cell using the Zemax program for different aspect ratio ($A.R$) values and incident angles of the rays against another cell with triangular grooves and no mirrors. For $A.R$=1,with a parallel incidence angle of the triangular grooves of$\theta^{\circ} = 50^{\circ}$, the number of rays that hit the detector is equal to2998 in the case of using mirrors. However, it was equal to 1200 without mirrors with across incidence angle of the triangular grooves of$\theta^{\circ} = 20^{\circ}$and $A.R$ =1thenumber of rays for the case using mirrors was equal to 2960,and 1000 without mirrors.

Keywords: *Solar cell, Mirrors, Zemax, Incident angle,Grooves, Aspect ratio.*

الملخص :كفائة الخلية الشمسية تعتمد على كمية اشعة الشمس الساقطة على سطحها والانعكاس داخل الخلية . أستخدمت طرق مختلفة لتحسين كفاءة الخلية الشمسية . في هذا البحث ، استعملنا الاخاديد المثلثة على السطح العلوي لخلية السليكون لتقليل الانعكاس الخارجي على سطح الخلية ولزيادة الانعكاس الداخلي داخل الخلية وضعت مرآيا على الجوانب الاربعة للخلية . بأستخدام برنامج الزيمكس سنقارن اداء هذه الخلية مع خلية اخرى ذات اخاديد مثلثة فقط دون مرآيا لقيم مختلفة من نسبة المظهر ( ) A.Rوزوايا سقوط الاشعة. لقيمة نسبة مظهر =1 مع زاوية سقوط موازية لسطح الاخاديد ومساوية ($\theta^{\circ} = 50^{\circ}$) ، فأن عدد الاشعة التي تضرب الكاشف مساوية 2998 في حالة استخدام المرآيا . في حين تكون مساوية 1200 شعاع بدون استخدام المرآيا . مع زاوية سقوط تقطع سطح الاخاديد المثلثة ($\theta^{\circ} = 20^{\circ}$) ونسبة مظهر =1 فأن عدد الاشعة تكون مساوية 2960 في حالة استخدام المرآيا و 1000 شعاع بدون استخدام المرآيا .

1. Introduction

The problems of global warming and pollution leads the world to interest insearching for alternatives to the fossil fuels, the exploring renewable energies has grown in the last years due to the energy crisis and protection the environment.

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Solar energy systems based on photovoltaic cells (PV) sources have attracted a lot of attention in the recent years due to their abilities of generating clear, clean andlimitless energy. PV sources are predicted to have the highest increase 30% in the next decade and to be the biggest contributor on the electricity generation in 2040 [1]-[4].

Light energy can be converted to electrical energy, without generating any undesirable side effects, by using an electrical device called a solar cell [5]. Silicon is the most important component of a solar cell construction [6]. The solar cell equivalent circuit is shown in Figure (1), which is consist of current source, diode, shunt resistance and series resistance [7].

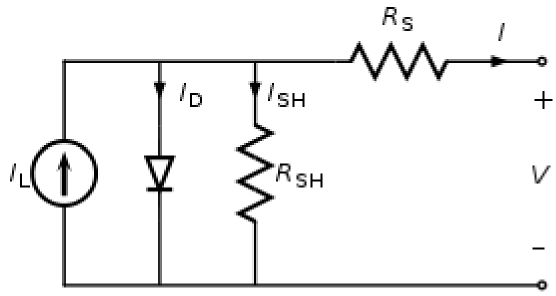

Figure 1. Solar cell equivalent circuit.

From the equivalent circuit shown above we can find the current produced by the solar cell (*I*) is equal to current produced by the current source (I_L), minus the current which flows through the diode (I_D), also minus the current which flows through the shunt resistor (I_{SH}).

$$I = I_L - I_D - I_{SH} \qquad (1)$$

Where
I = Output current (Amp.)
I_L = Photo generated current (Amp.)
I_D = Diode current (Amp.)
I_{SH} = Shunt current (Amp.)
The current through these elements is ruled by the voltage across them:

$$V_j = V + IR_S \qquad (2)$$

Where
V_j = Voltage across both diode and resistor R_{SH} (Volt)
V = Voltage across the output terminals (Volt)
I = Output current (Amp.)
R_S = Series resistance (Ω).
By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_O \left\{ \exp\left[\frac{V_j}{n\,V_T}\right] - 1 \right\} \tag{3}$$

$$V_T = k\,T/q$$

Where
I_O = Reverse saturation current (Amp.)
n = Diode ideality factor (1 for an ideal diode)
q = Elementary charge(Coulomb)
k = Boltzmann's constant
T = Absolute temperature (°C)
By Ohm's law, the current diverted through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}} \tag{4}$$

Substitutingequations (2), (3) and (4) in (1) produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage [8]:

$$I = I_L - I_O \left\{ \exp\left[\frac{V+IR_S}{n\,V_T}\right] - 1 \right\} - \frac{V+IR_S}{R_{SH}} \tag{5}$$

Due to the characteristic equation we can draw the *I-V* characteristic for the solar cell for certain solar radiation, which can be shown in the figure below [9, 10]:

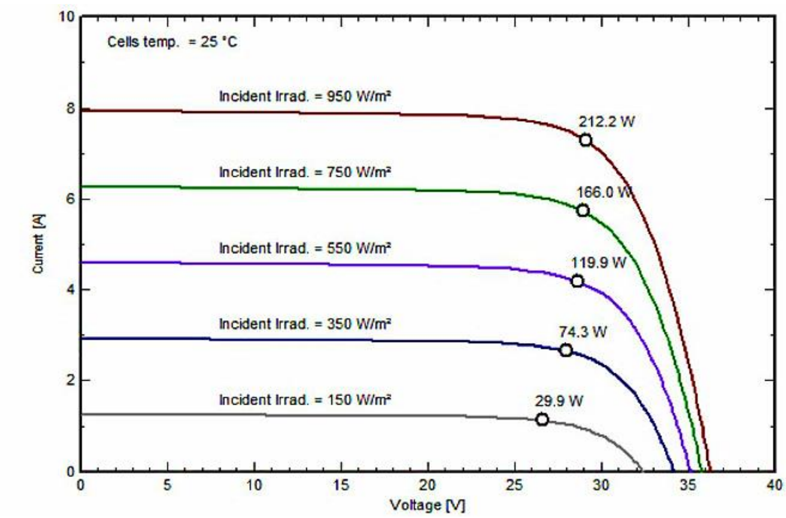

Figure 2. Solar cell I-V characteristic.

Whena solar cell is exposed to light, it can generate current without using any external voltage sources [5].Solar cell efficiency depends on the amount of sunlight falling on its surface. Different methods are used to improve solar cell efficiency. One of these methods uses solar concentrators. Mirrors and Fresnel lenses are used to increase the concentration of radiation on the silicon surface [11].

Multimode slab waveguide and two–dimensional lens arrays are used to demonstrate a solar micro-optic concentrator [12].An anti-reflection layer can be added onto the surface of the silicon to reduce the reflection losses of the surface and thusimprove the cell's efficiency [13].Texturing the silicon surface to reduce to the reflection of rays and increasingthe optical path length through the cell, then increasing the absorption of the photons within the cell, is another way of enhancing the solar cell. Figure (3) shows how the optical path is increased by texturing the silicon surface [14].A wet acid surface texture method is used for solar energy, which is easy to work with, in addition to its low cost and high efficiency. However,this method is an important factor for environmental pollution [15].

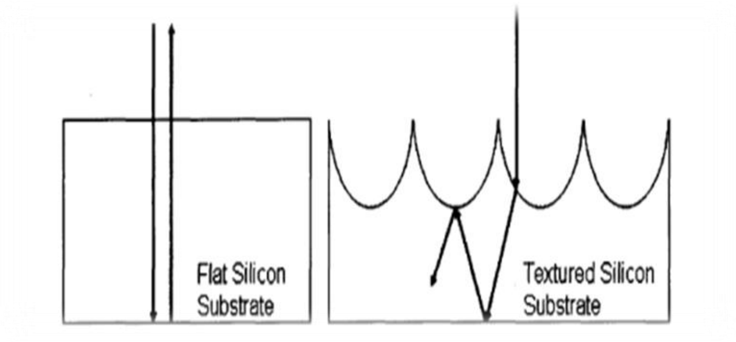

Figure 3. Effect of texture the surface of silicon on the length of optical.

An important topic, which has contributed towardsthe development of solar cell efficiency, is the use of grooves on the upper or lower surfaces of the cell; in order to reduce the proportion of outside reflections of radiation onto the surface of the cell. It increases the internal reflection within the cell and lengthens the optical path. These grooves may be rectangular, spherical, hierarchical triangular or parabola in form [11]. Figure (4) shows how triangular grooves reduce the reflectivity of the solar cell [6]. In 2007, parabolic and semi-circular cross-section grooves were used by C.W.Ruggiero to design a new texturing pattern for silicon solar cells using the Zemax program to track light paths by light striking the cell’s surface [11]. In this paper, we used triangular grooves on the upper surface of the silicon cell, along with mirrors on the four sides of the cell and compared the performance using the Zemax program against another similar cell but without mirrors.

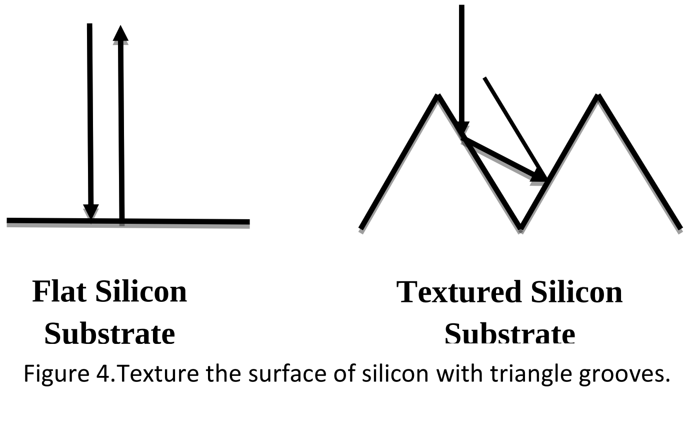

Figure 4.Texture the surface of silicon with triangle grooves.

2. Experimental Work

In this work, in order to improve the efficiency of silicon solar cells by increasing the internal reflection within the cell,triangular grooves were placed on the upper surface of the cell in addition to placing mirrors on four sides (i.e., left, right, front and back) of the cell (as shown in Figure (5)). The dimensions used to design the silicon solar cell in this work were 10cm x 10cm x 0.5cm [16].The triangular grooves were used to reduce the outside reflection of rays onto the surface of the cell; thus increasing theinternal reflection and optical path length within the cell . Placing mirrors on the sides of the cell allowed additional reflections within the cell;thereby increasing the number of rays and optical path length, and consequently improving efficiency.These mirrors made it difficult for rays to exit from the sides of the silicon cell.

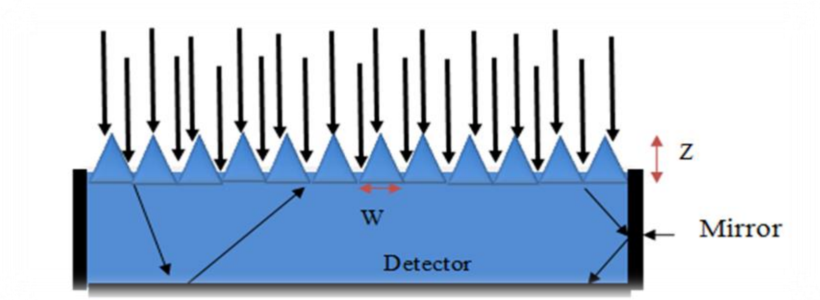

Figure 5. Texture the surface of silicon with triangle grooves and putting Mirrors on the sides of the cell.

An infrared ray (IR) sensitive detectorand visible light was placed on the bottom surface of the cell. These had the same dimensions (length and width)as the cell. This detector was used to calculate the number of rays that hit the bottom of the cell and therefore calculate the length of the optical path within it; as per the following equation[16]:

$$L = 2R \tag{6}$$

Where$L$ is the optical path length and R is the number of rays that hit the detector.

In this work, the grooves were designed with different width (W) values and a fixed length (Z) (as shown in Figure 6). This variation led to various values of aspect ratio ($A.R$) according to the following equation:

$$A.R = Z/W \tag{7}$$

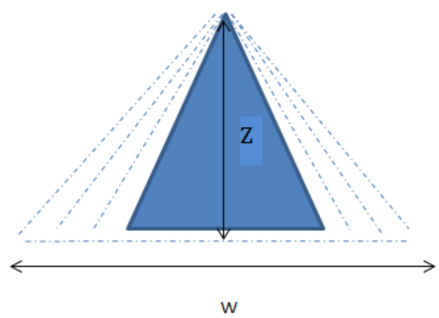

Figure 6. Triangle silicon grooveswith variable base.

The software program used for the design of the silicon solar cell,known as Zemax, hasa non-sequential ray tracing mode.

The system parameters used for both the design and the simulation results are shown in Table (1).

Table (1): System parameters.

Parameter	Value
No. of rays	1000 rays
Vertical incident angle $\boldsymbol{\theta}^{\circ}$	0°
Incident angle θ (degree)	$(10-80)^{\circ}$
$\boldsymbol{A.R}$	(0.5,0.6,0.7,0.8,0.9,1,1.2,1.4,1.6,1.8 and 2)

3. Results and Discussion

The effect of different aspect ratio ($A.R$)values and ray incident angleson the efficiency of solar cells, with and without mirrors, are introduced in this section.For each aspect ratio value, only the base of the triangular grooves is varied.

Cell efficiency is determined by reading the detector, located below the cell,which calculates the number of rays falling on it.

3.1. *Performance of Silicon Solar Cell for Different Values of (A.R) with Parallel Incidence Angle of the Triangular Grooves.*

The numbers of rays that hit the detector in cells, with and without mirrors, for different $A.R$values, with parallel incidence angle of the triangular grooves, are shown in Figures (7) and (8), respectively.

Figure (7) shows that for all values of $A.R$and $\theta^{\circ}=0^{\circ}$ (incident angle is vertical of the cell), the detector reading is better than that shown in Figure (8).

Furthermore, for $A.R$=1,1.4,1.6 and θ°=50°,50° and 20° the number of rays that hit the detector is equal to2998,2818 and 2017 rays,respectively. Meanwhile, in Figure(8), it is equal to 1200,800 and 1800 rays, respectively, for the same values of $A.R$ and θ°.

This difference is due to the use of mirrors in addition to triangular grooves.As the placement of the mirrors on the sides of the cell prevents the exit of radiation from its sides, this allows the raysto be exposed to additional reflections within the cell;thereby increasing the number of rays and the optical path length; thus improvingcell efficiency.

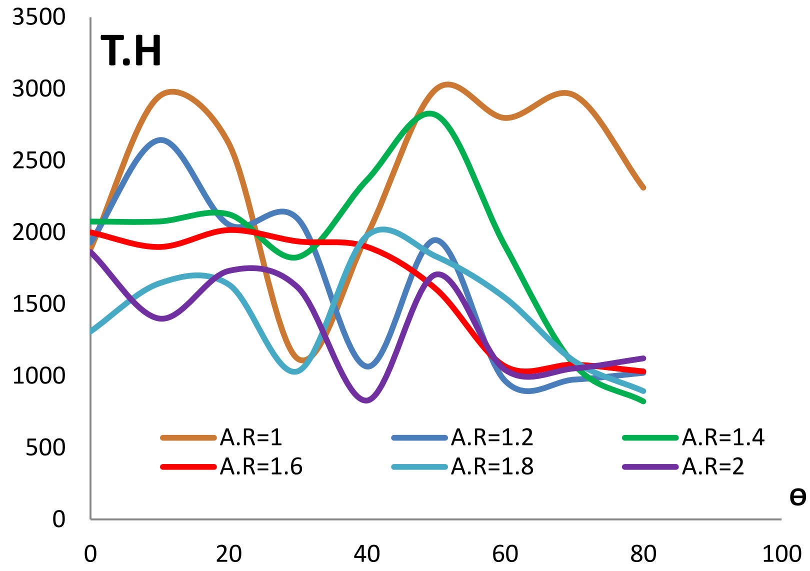

Figure 7. The number of rays that hit the detector in cell with using mirrors for different values of (A.R) with parallel incidence angle of the triangular grooves.

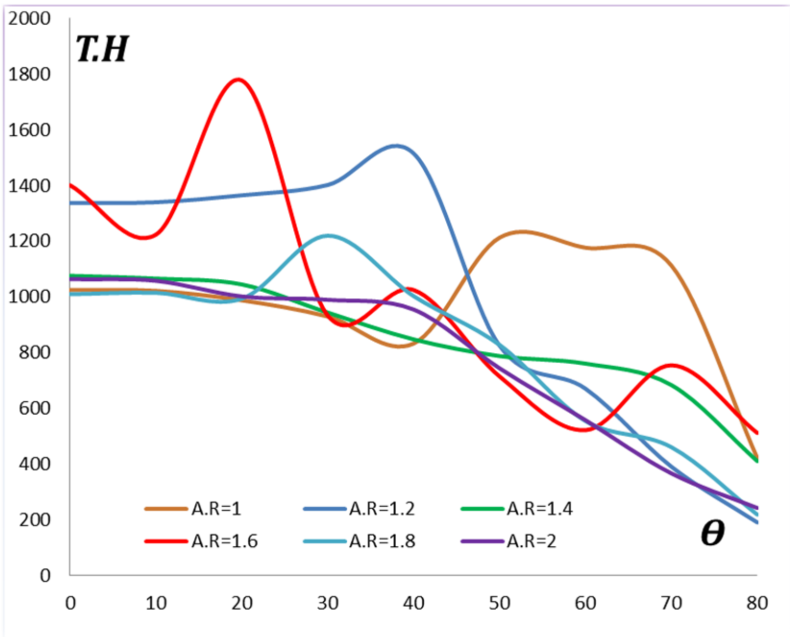

Figure 8. The number of rays that hit the detector in cell without using mirrors for different values of (A.R) with parallel incidence angle of the triangular grooves.

3.2. *Performance of Silicon Solar Cell for Different Values of $(A.R)$ with Cross Incidence Angle of the Triangular Grooves.*

The numbers of rays that hit the detector in cells, with and without mirrors, for different values of $(A.R)$, with crossincidence angle of the triangular grooves, are shown in Figures (9) and (10), respectively.

Figure (9) shows that forcross incidence angles of the triangular grooves from θ°=($10^{\circ}$to 40°), the detector reading is better than that shown in Figure (10); where, for $\theta^{\circ}=20^{\circ}\,to\,30^{\circ}$and $A.R$=1,1.4, the number of rays is equal to 2960 and 2750, respectively, in the case of using mirrors,and equal to 1000 and 1200 rays, respectively, without mirrors. Hence, the efficiency of the solar cell in the case of using mirrors is better than the cell that uses triangular grooves without mirrors.

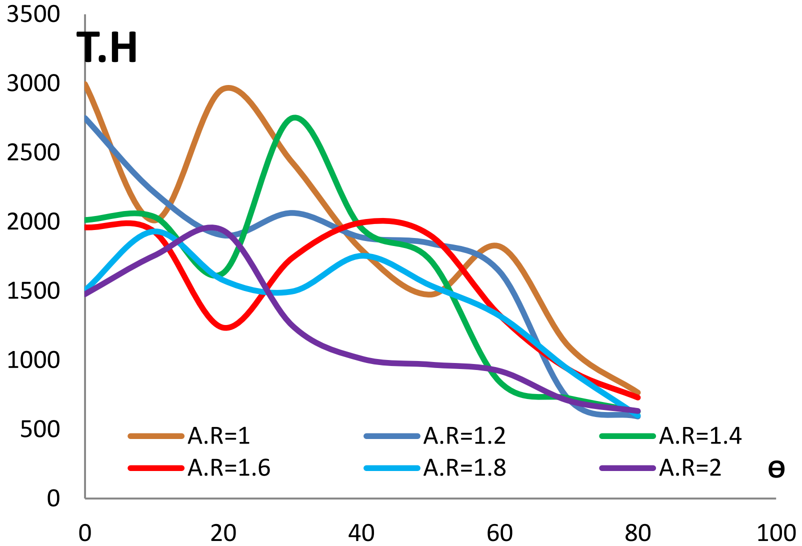

Figure 9. The number of rays that hit the detector in cell with using mirrors for different values of (A.R) with cross incidence angle of the triangular grooves.

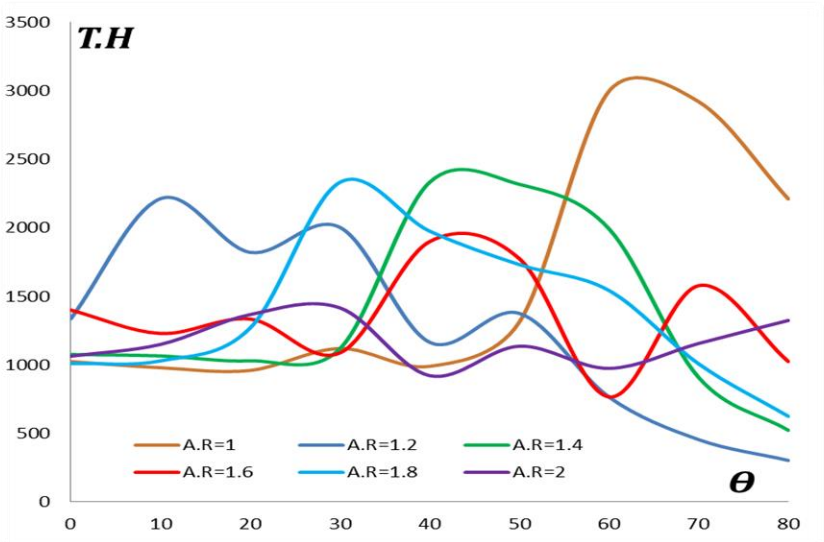

Figure 10. The number of rays that hit the detector in cell without using mirrors for different values of (A.R) with cross incidence angle of the triangular grooves.

4. Conclusions

In order to improve the efficiency of silicon solar cells, triangular grooves are placed on the upper surface of the cellwith mirrors placed on the four sides of the cell**.**The Zemax program, with non-sequential ray tracing mode, was used to design the silicon solar cell. The simulation results show that the performance of silicon solar cells that use mirrors is better than cells that use grooves without mirrors. This result is attributed to the fact that placing mirrors on the four sides of the cell allow the raysto be exposed to additional reflections within the cell; thereby increasing the number of rays and the optical path length; thus improving cell efficiency.

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