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Investigation and Simulation of the Effects of Dispersion and Transmittance angles on the Solar Cells Quantum Efficiency

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Abstract: In this paper the effects of transmittance, dispersion angle and diffusion length on the quantum efficiency of solar cells (QESC) have been simulated and investigated. Optical path technic is used for simulation. The results show that base thickness, diffusion length, dispersion angle, number of optical confinement path and transmission angles have an extremely effects on the QESC. Simulation results show that for $\boldsymbol{4n_{Si}^2}$optical paths with $\boldsymbol{\varphi = \theta_l = 0°, 30°, 60°}$and $\boldsymbol{\theta_l = 60°}$ QE can be achieved to 72% which is approximately 12% more than$\boldsymbol{\theta_l = 0°}$. The simulation results with grating in SC and reflecting about 100% at the end of the device show that QE increase to ٪47 with $\boldsymbol{\theta_m = \theta_l = 60°}$which is more than the results of device without grating. So the results show that the QESC increase with increasing the dispersion angle and diffusion length in the grating device.

Keywords: diffusion length, maximum dispersion angle, optical confinement, transmission angle.

1. Introduction

In order to increase the normal solar cells efficiency, different views and various plans can be used. Optics is one of the most significant branches to improve solar cells efficiency in which optical lenses are used to centralize the light effectively on the absorbent zone. Reduction of light reflection from the panel surface which causes light coverage path increase can also be assumed as another optical plans aim. Therefore light trapping plans from optical point of view can be classified as solar cells so that much light for a longer period of time would be kept inside the panel. The more it is possible for the light to travels inside the solar cell, be trapped for a longer period of time, the more probable it is to absorb photons and consequently more electron-hole pairs are

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formed. One of the main advantages of this method is decreasing the thickness of absorbent layer that can effectively reduce final construct expenses.

Light Trapping Technique

Light trapping plans often focus on increasing short circuit of solar cells. This phenomenon would be possible by increasing the light absorption in absorbent layer. Light absorption and short circuit are related through (1).

$$J_{sc} = \frac{q}{hc}\int \lambda' A(\lambda') Irrd(\lambda') d \tag{1}$$

In which, J_{sc} stands for short circuit current density, q for electron bar, h for *Plank's* constant measure, c for light speed, λ for wavelength, A for silicon structureabsorption and*Irrd* represents radiationspectrum. So, increasing the absorption which results in short circuit current increase will directly augment the solar cell efficiency. In conclusion, short circuit current is supposed to be one of the most significant parameters for efficiency evaluation.

Light Trapping Limits

After finding an efficiency criterion, short circuit current, it is desirable to identify the factors which may limit augmenting this parameter. Identifying the limits canbe helpful to determine the methodology through which an improved structure planningwould be obtained. In silicone solar cell studies, the range of wavelength is usually between 400*nm* and 1000*nm.* If in this range, silicon absorption is supposed 1, then according to (1) short circuit current equals 43.12mA/cm^2, which indicates maximum short circuit current in this range. Another limit for short circuit current, as illustrated in Figure1, is its 5*mn* silicon structure without usinglight trapping plans. If a reflector is placed at the end of the base zone to reflect the light normally, then the light path length which is the effective thickness of the panel, equals 2.

Maximum light path length can be calculated by using statistical mechanics in optical structures with heterogeneous thickness. The optimal maximum light path length is $4n^2$ which is the refraction coefficient of the material being used. If refraction coefficient of silicone is assumed 3.5 then maximum light path is about 50. Considering the light path limits, maximum absorption is calculated through relation (2).

$$A(\lambda) = 1 - \exp\left(-\alpha_s(\lambda) 4 n_s^2(\lambda) W_{eff}\right) \tag{2}$$

where α_s is absorption coefficient of silicon, n_s is its refraction coefficient and W_{eff} is the effective thickness of the panel.

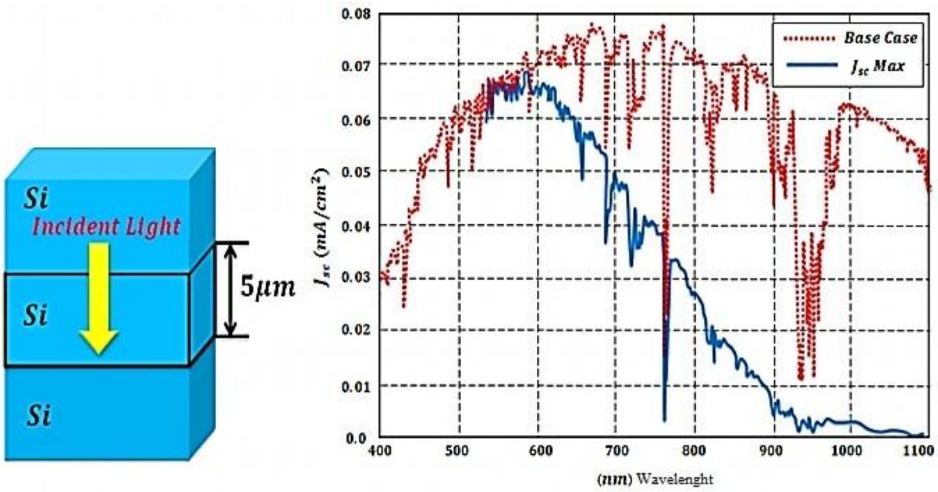

Fig. 1. light passage through 5mn silicon structure and its short circuit curve.

Light Trapping Optics

This part aims to investigate the various structures for light trapping in silicon solar cells. The path which light passes through the air to reach the point on the absorbent layer where photon is absorbed is very important and has attracted a lot of attention. In the air, Light wave with passage coefficient 1 is weakened and reflected very slightly. However, due to great difference between air and panel surface refraction coefficients, a part of light is reflected, a part is absorbed and the third part is transmitted into the panel. These three phenomena form the basic principles of the Science of light Trapping. So in order to understand the light trapping mechanism well, some important plans including anti-reflective cover, back reflector and dispersion grating are going to be discussed.

Simple Silicon

Figure2 illustrates a piece of crystalized simple silicon which light is radiated on vertically. Simple silicon means silicon without any cover. First thing learnt from figure2 is the reflection of a great deal of light from the silicon surface.

Light reflection from the silicon surface is because of the difference between refraction coefficients of silicon and air. For example for a 900*nm* wavelength, air refraction is 1 and refraction coefficient of silicon is 3.6; then reflection coefficient at the boarder of silicon and air can be calculated through ***Fresnel's*** function:

$$\Gamma_{12} = \frac{n_1 - n_2}{n_1 + n_2} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \tag{3}$$

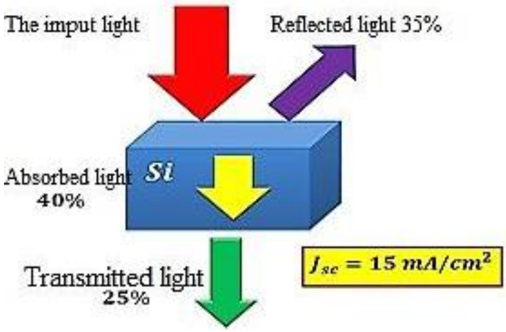

Fig. 2. The schema of the incident light radiating a piece of simple silicon.

where Γ_{12} is reflection coefficient, n_1 and $\eta_1$are refraction coefficient and impedanceof the first environment(air) and n_2 and $\eta_2$are the refraction coefficient and impedance of the second environment (silicon), respectively. Reflection coefficient is the ratio of the electric fields for reflected waveand the incident wave. Reflection measure, ratio ofreflected power density, is the domain square of the reflection coefficient. So crystal silicon reflection is a percentage of domain square of the reflection coefficient:

$$|\Gamma_{12}|^2 \times 100$$

For crystal silicon, the amount of reflection in a 900*nm* wavelength is 32.18% . it means that 32.18% of the incident light energy is wasted because of the light reflection from the panel surface. So the reflection needs to be minimized. Using dispersion matrix, the whole reflection can be calculated in a range of 400-1100*nm* that for silicon this amount is 35%. Considering the figure, it can be observed that only 40% of the incident light energy is absorbedby the panel which this amount is just for one wavelength and 25% of the incident light transmits the panel. If all 40% absorbed light photons transform to electron-hole pairs, assuming non-re-composition, then, $J_{SC}=15mA/cm^2$

Anti-ReflectionCoating

An important matter to be considered in designing and augmentingsolar cell efficiency is either increasing incident light transmission into the structure or decreasing reflection from the panel surface. One of the ways to decrease reflection and reflective waste in solar cells is using Anti-Reflection(AR) coating. An anti-reflection coating includes several layers which mainly are made of de electric materials. The idea of using transparent middle layers for reducing reflection goes back to the early 1800s. These middle layers are the buffers for great alterations between the material with small refraction coefficient and the material with large refraction coefficient. So in order to make AR coating in silicon solar cells, materials which their refraction coefficient is between refraction coefficient of air and refraction coefficient of silicon should be used so that light can be transmitted from air to silicon effectively.

Silicon with Anti-Reflection Coating

In this part like Figure3, a structure is supposed in which an AR coating is added to the simple silicon. For simplicity, refraction coefficient of the AR layer is considered as geometric mean of refraction coefficients of air and silicon in a 900nm wavelength. Thickness of this layer is also set at $\lambda_0/4n_2$. Considering these parameters for AR coating and according to Figure3, surface reflection decreases to the 8% of all incidents light. Similarly, absorption in silicon layer increases because more light has entered into the absorbent layer in comparison with simple silicon. Absorption has increased 57% comparing with of simple silicon, 17% increase has occurred. More power is expected to transmit the panel when an AR coating is used. According to Figure3, this amount has increased 10% in comparison with using no AR.

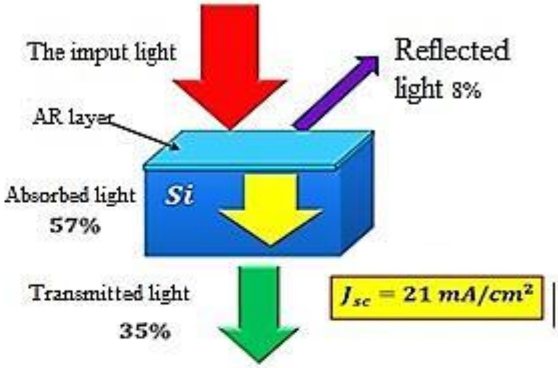

Fig.3. The schema of the incident light radiating a piece of simple silicon which is coated with a layer of AR.

Silicon Band Edge

Silicon has a non-straight band structure so in wavelengths near to its band split, it has weak natural absorption. Let’s focus on wavelength range of 850-1100nm which is near to the silicon band. 23% of the whole power is in this range. However, only 8.7% of this amount is absorbed inside the panel through a light path. (This amount is only 2% of the whole power in the range of 400-1100nm). For thin-layer silicon solar cell, other light trapping plans in absorbent layer are needed to maximize the absorption and minimize the passing power. By adding ideal back reflector to the silicon solar cell structure, no power would pass through the panel.

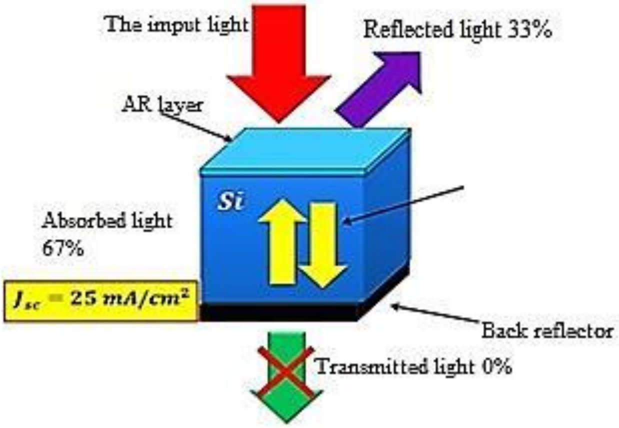

Fig. 4. The schema of the incident light radiating a solar cell with an AR layer and back reflector.

In this manner, the power that used to pass through is returned to the absorbent layer is absorbed again. Therefor by using back reflectors, the passing light path length through the solar cell is doubled and absorption 10%decreases. In fact, by increasing the light path length, the effective thickness in the active area has increased and consequently photons are deeply absorbed in the active area.

Dispersion Grating

Dispersion Grating phenomenon is based on the occasion when light arrives splits and grooves with intermittence similar to its wavelength. A dispersion grating is an intermittence of these splits. Any of the splits plays the role of a light source that is to say they either reflect or transmit light.

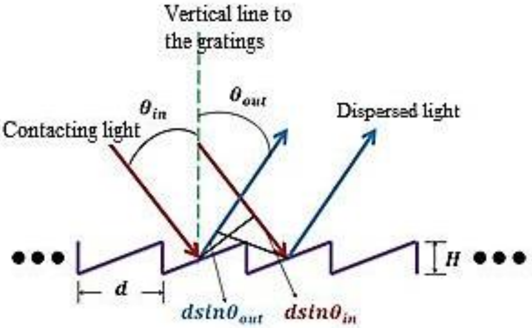

Fig. 5.The schema of the incident light radiating a dispersion grating; distance discrepancy between incident light rays and dispersed light rays is the basis of dispersion grating equations.

Dispersed light waves interfere effectively and positively in a particular angle with the vertical line to the gratings. This angle is determined according to the grating dimensions. In practice, it is difficult to find a simple analytic way to obtain the grating parameters due to grating material changes, diverse dimensions and dispersion index of the materials being used. So in order to maximize the grating qualities, numerical methods are often used which Dispersion Matrix is one of the existing ones.

Silicon with AR coating, Back Reflector and Dispersion Grating

By installing dispersion grating on the solar cell, light path length increases significantly. The light which reaches the grating at the end of the absorbent layer, is dispersed on different degrees and diverse modes with a greater angle in comparison with silicon’s critical angle. This results in complete internal reflection so light returns into the absorbent layer. Then, after passing again through the absorbent layer, the light hits the grating is dispersed for another time. Considering the Figure, this process is repeated for several times. Using a one-dimensional(linear) gratings are not only easy to make but also able to be used in both kinds of polarization. The Figure shows the solar cell structure where all three ideas of AR coating, Back reflector and dispersion grating are used. In this situation, absorption comparing with the only use of AR and BR has 17% increased. It should be considered that the total absorption has doubled comparing with non-trapping solar cell structure. Using this structure, J_{sc}=35mA/cm^2 which compared to a similar structure but without dispersion grating, has 10mA/cm^2 increased.

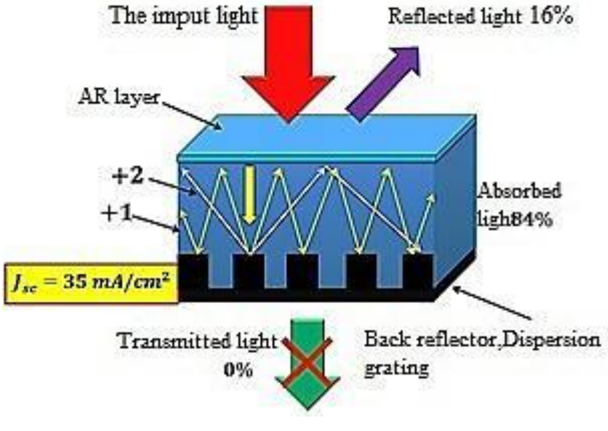

Fig. 6. The schema of the incident lightradiating a solar cell with an AR layer, Back reflector and Dispersion Grating**.**

In the structure of Figure6, reflection also has increased because of dispersion at the zero time when a part of incident light is reflected at the radiation angle and since the dispersion angle at this stage is smaller than critical angle, it goes out the panel directly.

2. Simulation

Figure7 illustrates a silicon solar cell in which dispersion grating and back reflector for light trapping at the base zone are used. Due to incident light dispersion by gratings, the grating path has lengthened and the probability of absorption at the base layer has increased. The dispersed light by gratings reflects and hits the upper layer again with the angle θ_m. Considering complete internal reflection, the light reflects again with angle θ_l inside the panel. A part of light rays which radiate the panel vertically will reflect with the same angle from the grating surface and will exit the cell after hitting the upper surface of the panel because the angle of incidence they make with vertical line on the upper layer is smaller than the critical angle. On the other hand, light current is extremely dependent on quantum efficiency intensity. Obtaining Quantum Efficiency (QE) is very useful for assessing the cell's function. Quantum Efficiency includes Internal Quantum Efficiency(IQE) and External Quantum Efficiency(EQE).Internal quantum efficiency (IQE) is the ratio of the number of minority vectors participating in short circuit current to the number of photons entering inside of the panel. Quantum efficiency needs to increase so that solar cell transforming efficiency increases consequently.

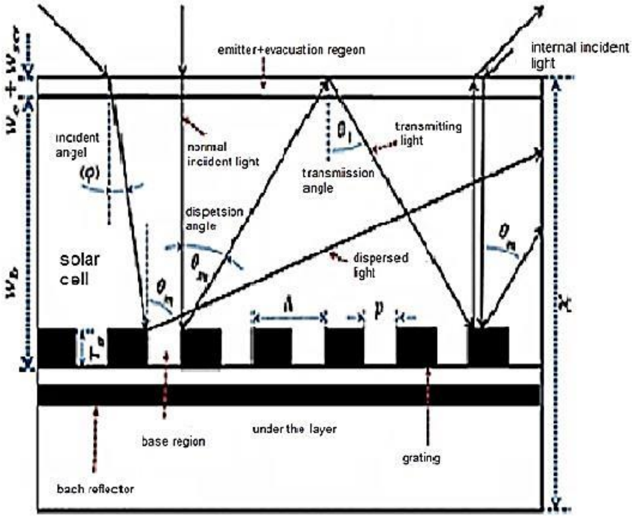

Fig. 7. Solar Cell Panel with a Grating Structure.

Penetration Length Effect

In order to analyze the effect of penetration length(L_b) on quantum efficiency, thickness amounts in evacuation and emitter areas are assumed w_{scr}= 1.0µm and w_e=0.5µm. Base thickness varies in the range of w_b=0-1000µm and quantum efficiency is simulated as a function of base thickness. The total thickness is calculated through$H=w_b+w_{scr}+w_e=w_b+1.5$µm.At this stage just the normal incident light, $\varphi=0$, is supposed. L_b penetration lengthvaries from 25µm to

1000μm and its effect on quantum efficiency is analyzed. Figures 8 to 10, illustrate the results of quantum efficiency simulationin terms of base thickness for 1000nm,1050nm and 1100nm wavelengths respectively. For each figure, 6 quantities of L_b have been considered.

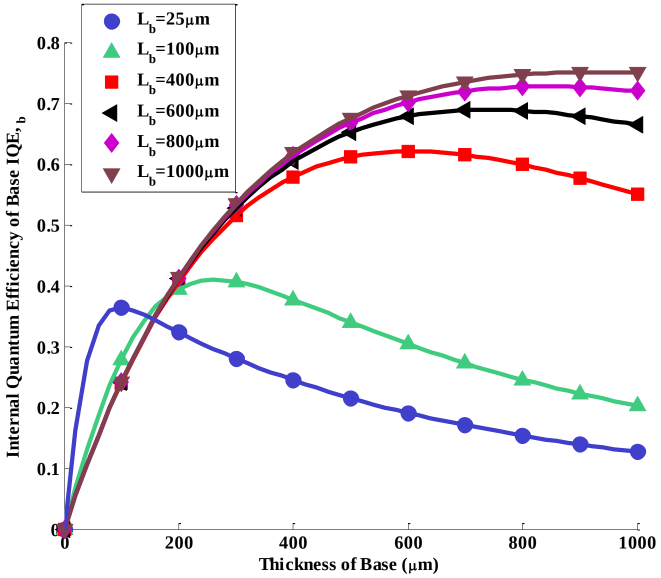

Fig. 8. Quantum Efficiency in terms of Base Thickness for variouspenetration length in it he incident wavelength 1000nm.

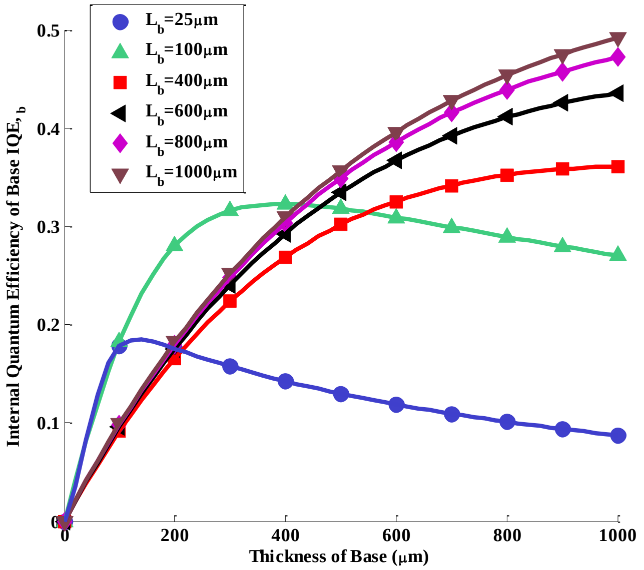

Fig. 9. Quantum Efficiency in terms of Base Thickness for variouspenetration length in it he incident wavelength 1050nm.

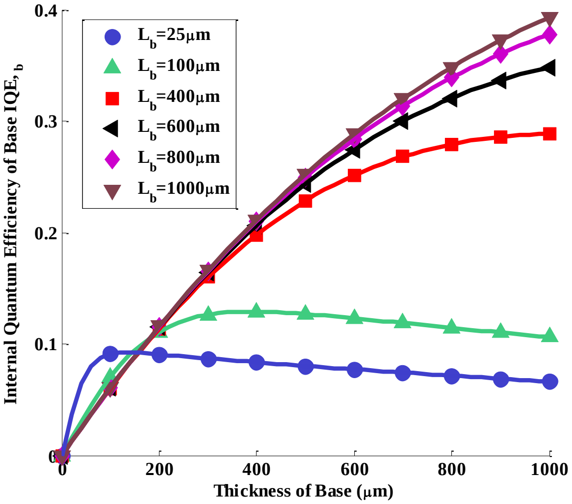

Fig. 10. Quantum Efficiency in terms of Base Thickness for variouspenetration length in it he incident wavelength 1100nm.

Considering Figure10, and as it was expected, increasing L_b causes increase in quantum efficiency. For L_b=1000μm, quantum efficiency in terms of L_b=400μm ,L_b=100μm and L_b=25μm is respectively 15% , 37%and 40% much more.For L_b=1000μm the maximum quantum efficiency in terms of base thickness, w_b=1000μm, is about 75%. Figure9 shows similar results to of Figure8 for incident light with wavelength of 1050nm. Since absorption coefficient of silicon decreases in this wavelength, the obtained quantum efficiency is smaller than that of the 1000nm wavelength. Figure 9 shows similar results for light with wavelength of 1100nm.Absorption coefficient of silicon decreases in this wavelength so the obtained quantum efficiency is less smaller than those of 1000nm and 1050 nm wavelengths. Considering Figure10, for penetration length of 1000, L_b=1000 μm, quantum efficiency in comparison withL_b=400 μm, L_b=100 μmand L_b=25 μm is respectively12%,28% and 30% more. For L_b=1000 μm, the maximum quantum efficiency in terms of base thickness of w_b=1000 μm, is about 40%.

The effect of transmission angle

Considering the parameters in Table1, dimensions of the solar cells are determined as w_{scr}=1.0μm, w_b=300μm, w_e=0.5 and the penetration length,100μm, L_b=100 μm.

Table1. Structural and Electrical Parameters of Cell

velocity	**Penetration length(μm)**	**Penetration coefficient($cm^2/2$)**	**Thickness (μm)**	**Region**
1×10^4	5	5	0.5	Emitter(w_e)
			1.0	Evacuation rege(w_{scr})
1×10^7	25-1000	30	0-1000	Base(w_b)
			W_b+1.5	Total thickness(H)

In order to study the effect of transmission angle, quantum efficiency in terms of the number of light paths is simulated. The maximum number of paths is $4n^2=51$. Simulation for three different measures of transmission angle, $\theta_l=0^\circ$, 30° and 60° is performed. Figure11 shows the results. To show the effect of light trapping in a cell with a great transmission angle, the quantum efficiency results are determined as a function of the number of the light paths for incident wavelength ranging 950-1200 nm.

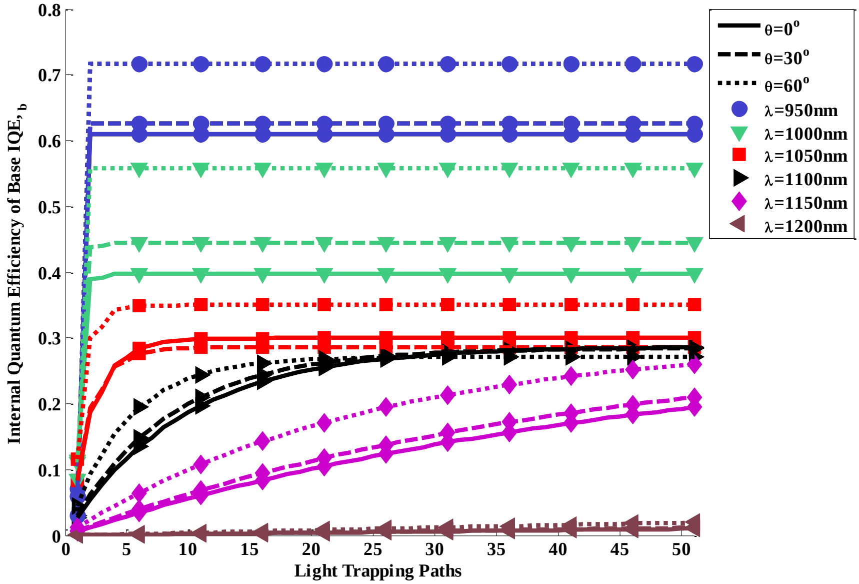

Fig. 11.Quantum Efficiency in terms of the number of light paths for three measures of transmission angle ($\theta_l=0^\circ$, 30°, 60° and incident wavelength of 950-1200nm).

Considering Figure11, for λ=950 nm,1000 nm, quantum efficiency at first increases with a great gradient then it is saturated from two light path sources then stays at a fixed amount. For λ=1050nm and 1100 nm, quantum efficiency respectively for 5 and 25 light paths is saturated. And for λ=1150 nm and 1200 nm, quantum efficiency increases with a mild slope and will not be saturated even with 51 light paths. It is also known that quantum efficiency with transmission angle of $\theta_l=60^\circ$ for λ=950nm in terms of $\theta_l=30^\circ$ and $\theta_l=0^\circ$, is respectively 10% and 12% greater. And for $\theta_l=60^\circ$ and $\lambda=1000$nm in terms of $\theta_l=30^\circ$ and $\theta_l=0^\circ$,is respectively 10% and 15% greater. For $\lambda=1050$-1150nm, quantum efficiency with transmission angle of $\theta_l=60^\circ$ in comparison with $\theta_l=30^\circ$ and $\theta_l=0^\circ$, is just a little more. Quantum efficiency for wavelengths of 950nm and 1000nm, due to high silicon absorption, in comparison with other wavelengths is much greater.

The Effect of Dispersion Angle

In this part, the effect of dispersion in a cell with grating is being discussed. At this stage some light trapping paths in the solar cell with a grating structure(made of $sio_2(n_{sio2}=1.46)$) and normal incident light, $\varphi=0^\circ$ are assumed.Considering the figure, the alteration period of grating structure is $\Lambda\sim800nm$ $(p\sim400nm)$and dispersion rank is assumed m=1 .The incident light which enter the solar cell with the angle of $\varphi=0^\circ$, is considered as the first light path. Reaching the end of the solar cell, this light ray is reflected by gratings into the solar cell under the dispersion angle of $\theta_m=60$. This light reflection is considered the second path. When the reflected light reaches the surface again, reflects into the panel with transmission angle of $\theta_l=60^\circ$. The light reflection from the panel surface is the third path. The fourth path is the path which the light of the third path after reaching the end of the panel is reflected by the gratings under the dispersion angle of $\theta_m=0^\circ$. This process of light trapping paths for any desired number of light paths can be repeated.

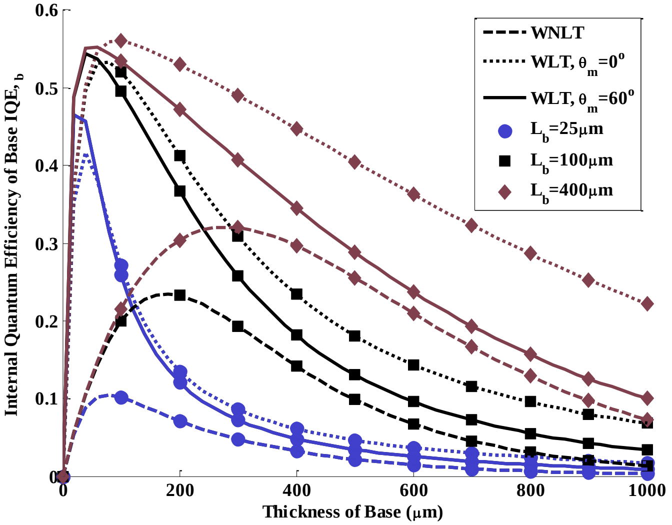

Fig. 12.Quantum Efficiency in terms of Base Thickness for threepenetration lengthsL_b=25,100,400µmand for three Dispersion Angle $\theta_m=0^\circ$, with nonlight trapping (WNLT). $\theta_m=0^\circ$, with light trapping (WLT) and $\theta_m=60^\circ$without light trapping (WLT) and incident wavelength 1000nm.

Considering Figure12, quantum efficiency for L_b=400μmin comparison with L_b=25 μm and L_b=100 μm is greater. For L_b=25μm and L_b=100 μm, non-trapping light graphs, trapping light graphs and dispersion angle of 0° in terms of base thickness greater than about 300 μm, are very close to each other so it is concluded that with a dispersion angle of 0°,better quantum efficiency is obtained. Therefor the smaller the dispersion angle, the higher quantum efficiency is.

The highest quantum efficiency for incident wavelength of 1000μm and parameters of L_b=400 μm and θ_m=0° is about 56%. Figure13 shows similar results for the incident wavelength of 1050 μm. Considering the Figure it is learnt that even for L_b=400 μm, the quantum efficiency is the highest. When compared with Figure12, Figure 13 shows that graphs have smaller measures because of decreasing of absorption index of silicon. However, light trapping graphs show smaller decrease in comparison with non-trapping graphs. Considering Figure13, it is concluded that light trapping graphs in comparison with non-trapping graphs have a greater distance with the same graphs in Figure12.For any base thickness greater than 100μm, the smaller the dispersion angle is, the higher quantum efficiency is obtained. However, For any base thickness smaller than 100μm and dispersion angle of 60°, quantum efficiency is higher. The greatest quantum efficiency for incident wavelength of 1050μm and parameters ofL_b=400 μm and θ_m=60° is about 47%.

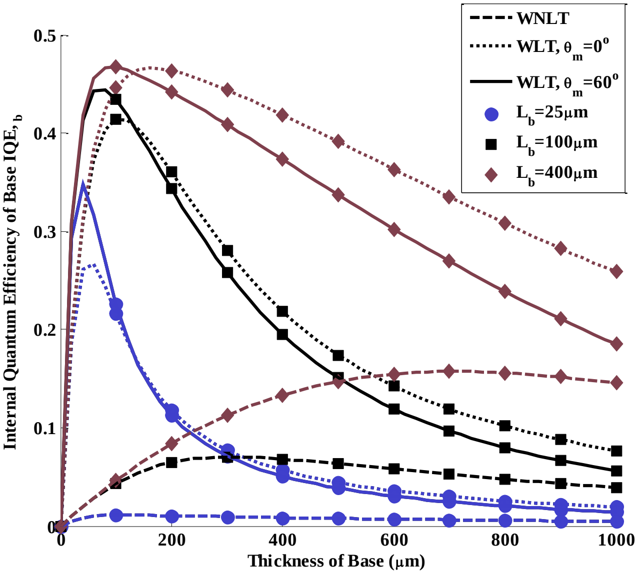

Fig. 13. Quantum Efficiency in terms of Base Thickness for threepenetration lengthsL_b=25,100,400μmand for three Dispersion Angle θ_m=0°, with non-light trapping (WNLT). θ_m=0°, with light trapping (WLT) and θ_m=60° without light trapping (WLT) and incident wavelength 1050nm.

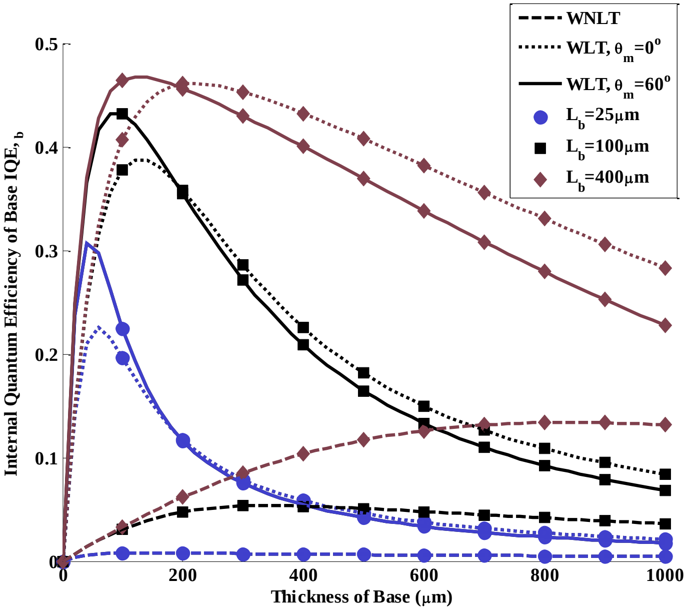

Fig. 14. Quantum Efficiency in terms of Base Thickness for three penetration lengths L_b=25,100,400μmand for three Dispersion Angle $\theta_m=0^\circ$, with non-light trapping (WNLT). $\theta_m=0^\circ$, with light trapping (WLT) and $\theta_m=60^\circ$ without light trapping (WLT) and incident wavelength 1100nm.

Figure14 states similar results for the incident wavelength of 1100μm. Again for L_b=400 μm, the quantum efficiency is the highest. In comparison with of Figure12, graphs have smaller measures due to decreasing of absorption index of silicon. The maximum quantum efficiency for incident wavelength of1100μm and parameters of L_b=400 μm and $\theta_m=60^\circ$ is about 47%.

3. Conclusion

Results showed that the base thickness, penetration length, dispersion angle, number of light trapping paths and transmission angle have significant effects on quantum efficiency of solar cells. Quantum efficiency increases when the number of light paths exceeds. However, base thickness was kept fixed at 100μm. To study the effect of penetration length(L_b), the highest quantum efficiency for L_b=1000 μm, is about 80% which is about 45% more than the quantum efficiency obtained for L_b=25 μm. Simulation results showed that for $4n^2_{si}$, the light path with transmission angle of ($\varphi=\theta_l=0^\circ$, 30° and 60°), and for $\theta_l=60^\circ$, quantum efficiency is about 72% which in comparison with$\theta_l=0^\circ$, is about 12% greater. By using a grating in the cell and reflecting nearly 100% of light at the end of the panel, simulation results showed that for a wavelength of 1050nm and dispersion angle of $\theta_m=\theta_l=60^\circ$, quantum efficiency increases to

47% which in comparison with a non-grating structure, $\theta_l=0^\circ$,$\varphi=0^\circ$,at the base thickness of $w_b=50\mu m$, is about 10% more. The results show that quantum efficiency will increase if dispersion angle and penetration length increase. For cells including a grating structure and thickness of $H>150\mu m$, quantum efficiency with dispersion angle of $\theta_m=60^\circ$ in comparison with dispersion angle of $\theta_m=0^\circ$ for all penetration lengths decreases due to small absorption index andvectors waste increase for high wavelengths. For short penetration lengths, increasing cell thickness causes more vector waste. For cell thickness of $H<150\mu m$, quantum efficiency of cells including a grating for $\theta_m=60^\circ$ in comparison with a non-grating cell and $\theta_m=0^\circ$, is greater. This phenomenon is due to increasingphoton absorption coefficient and decreasing vector waste in the range of high wavelengths.

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