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Theoretical Study of the Effect of the Diffusion Length of Electron on the Efficiency of the Single Crystal Silicon Solar Cell

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Abstract

This work includes a theoretical study to the effect of different diffusion lengths of electron on the parameters of the single crystal silicon solar cell.

Different values of diffusion length of electron are used and by using electronic calculator programme in visual basic language. The results show increasing the parameters of single crystal silicon solar cell with increasing the diffusion length of electron and consequently calculating the theoretical efficiency of the cell, which varied between (13.352 - 30.076) %.

The relationship between values of the diffusion length of electron and the input parameters in calculating the cell efficiency has been drawing and then drawing the relationship between these diffusion lengths and the theoretical efficiency of this cell as well as noticing effect of other parameters on that efficiency and important notes and conclusions is achieved which can be summarized in two features:

Firstly: Improving the diffusion lengths in both the top surface and the back surface would reduce losses due to bulk and surface recombination velocities at the front and back surface and bring measured photocurrents closer to the idealized values.

Secondly: Using a base layer of a thickness smaller than the minority carrier diffusion length, which improve the collection efficiency of the solar cell.

Keywords: Solar Cell, Silicon, Crystalline, Diffusion length, Efficiency.

1- Introduction

The increasing demand for fossil fuels and the environmental impact of their use are continuing to exert pressure on an already-stretched world energy infrastructure. Significant progress has been made in the development of renewable-energy technologies, such as solar cells, fuel cells, and biofuels. However, although these alternative energy sources have been marginalized in the past, it is expected that new technology could make them more practical and price competitive with fossil fuels, thus enabling an eventual transition away from fossil fuels as our primary energy sources. Solar energy is considered to be the ultimate solution to the energy and environmental challenge as a carbon-neutral energy source.

The conversion from solar energy to electricity is fulfilled by solar-cell devices based on the photovoltaic effect. Many photovoltaic devices have already been developed over the past five decades[1][2][3]. However, wide-spread use is still limited by two significant challenges, namely conversion efficiency and cost [4][5][6]. One of the traditional photovoltaic devices is the single-crystalline silicon solar cell, which was invented more than 50 years ago and currently makes up 94% of the market[7]. Single-crystalline silicon solar cells operate on the principle of p–n junctions formed by joining p-type and n-type semiconductors. The electrons and holes are photogenerated at the interface of p–n junctions, separated by the electrical field across the p–n junction, and collected through external circuits. In principle, the single

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crystalline silicon semiconductor can reach 92% of the theoretical attainable energy conversion , with 20% conversion efficiency in commercial designs . However , because of the considerably high material costs, thin-film solar cells have been developed to address the product costs[8][9][10]. Amorphous silicon (a-Si) is a candidate for thin-film solar cells because its defect energy level can be controlled by hydrogenation and the band gap can be reduced so that the light-absorption efficiency is much higher than crystalline silicon[11][12]

The problem is that amorphous silicon tends to be unstable and can lose up to 50% of its efficiency within the first hundred hours. Today, commercial roof products are available that operate at $\approx$15% efficiency. Bridging the gap between single-crystalline silicon and amorphous silicon is the polycrystalline-silicon film, for which a conversion efficiency of around 18% is obtained[13][14][15][16]. Compound semiconductors, such as gallium arsenide (GaAs), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), receive much attention because they present direct energy gaps, can be doped to either p-type or n-type, have band gaps matching the solar spectrum, and have high optical absorbance[17][18][19]. These devices have demonstrated single-junction conversion efficiencies of (16–32)% [20]. Although those photovoltaic devices built on silicon or compound semiconductors have been achieving high efficiency for practical use, they still require major breakthroughs to meet the long-term goal of very-low cost (US$0.40 kW / h)[1].

In this paper the effect of different diffusion lengths of electron on the parameters $(V_\circ, W, L_e, I_L, V_{oc}, I_{sc}, v_{oc}, FF)$ and then on the efficiency (η) of the single crystal silicon solar cell have been studied.

2-Theory

A solar cell can be constructed by putting a very thin, heavily doped *n*-type layer on top of a thicker *p*-type layer. As can be seen in Figure (1), the depletion region is mostly on the *p*-side. Light is absorbed through the *n*-type layer. Because the *n* layer is so thin, most photons penetrate into the depletion region, or the *p*-side before creating an electron-hole pair. When an electron-hole pair is created in the depletion region the electric field moves the electron into the *n*-side and the hole into the *p*-side. This gives the previously neutral *n*-side a negative charge and the previously neutral *p*-side a positive charge. When a load is connected to the cell, the electron can travel through the circuit, do work, and recombine with the hole.

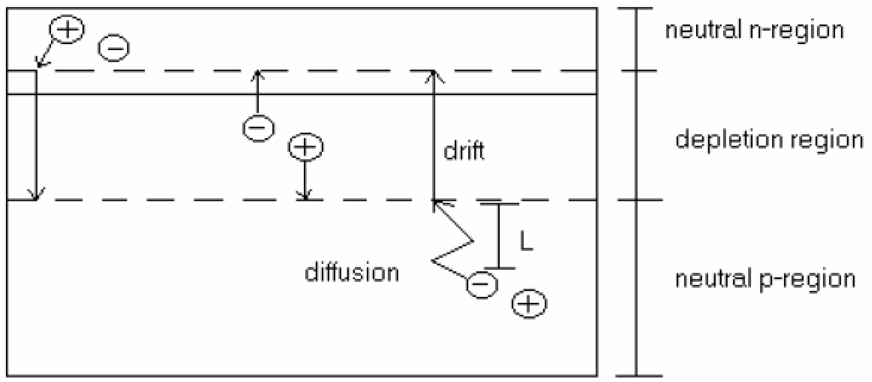

Figure (1): Electron-Hole Pair Behavior in Solar Cell [21]

If the light penetrates into the neutral *p*-side, then there is no electric field to separate the electron-hole pair. Instead the electron and the hole diffuse at random through the material and recombine if they meet. The average time between pair production and recombination for an electron is τ_e . In this time, the electron diffuses a mean distance of $L_e = \sqrt{2\tau_e D_e}$ where D_e is the diffusion coefficient in the *p*-side. If the electron-hole pair is created within L_e of the depletion region, then the electron can diffuse to the depletion region and be moved by the electric field over to the *n*-side. For this reason it is important for the diffusion length L_e to be as long as possible. The same process takes place for electron-hole pairs created in the *n*-side. In silicon, the diffusion length is longer for electrons than it is for holes. This is why the thin top region is *n*-type, and the thicker region is *p*-type[21].

Recombination by Doping :

The lifetime, calculated according to the recombination processes:

a- Band to band (Radiative) recombination.
b- Trap assisted (Shockley Read–Hall(SRH)) recombination.
c-Auger recombination).
is thus

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{radiation}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{trap}} \cdots\cdots\cdots (1)$$

All three depend to some degree upon dopant concentration. Figure (2) shows a summary of these dependencies.

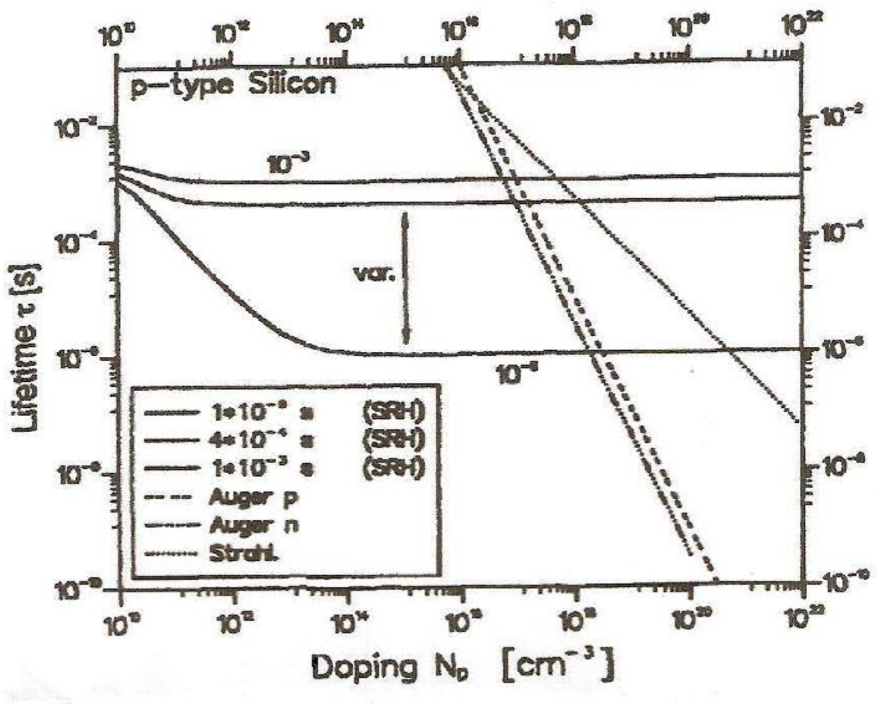

Figure (2): Dependency of the different charge carrier lifetime processes on doping

We again see that:

1-for doping less than 10^{17}cm^{-3} (normal for almost all Si devices) radiative recombination plays virtually no role, and carrier lifetime is determined by the impurity level.

2-only at doping levels greater than 10^{18}cm^{-3} does Auger recombination become dominant.

In the range 10^{16} to 10^{18} cm^{-3} there is a marked discrepancy between theoretical considerations and experimental results. This has already been investigated by [22]. The relationship obtained empirically by Kendall {quoted in[16]}, is frequently used at the moment, according to which the lifetime in this range is calculated as:

$$\tau = \frac{\tau_{\circ}}{1 + \dfrac{N_D}{7x10^{15}}} \cdots\cdots\cdots (2)$$

In this equation the carrier lifetime $\tau_{\circ}$ in pure, undoped silicon was previously assumed to be $400\mu s$.

Lifetime and saturation current measurements

The effective minority carrier lifetime, τ_{eff} , of a silicon wafer can be expressed as the sum of the recombination rates in the bulk and on the surface. The recombination rate is in general inversely related to the recombination lifetime, and the effective lifetime of a sample can be expressed as:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surface}} \cdots\cdots\cdots (3)$$

where τ_{bulk} and $\tau_{surface}$ are the bulk and surface recombination lifetimes, respectively. The recombination rate in the bulk can further be divided into the sum of independent recombination mechanisms via the inverse recombination lifetimes as:

$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{Aug}} + \frac{1}{\tau_{SRH}} \cdots\cdots\cdots (4)$$

τ_{rad}, τ_{Auger}, and τ_{SRH} are the radiative, Auger, and Shockley-Read-Hall recombination lifetimes, respectively. Since silicon is an indirect band gap semiconductor, radiative recombination is low and negligible to a good approximation. Auger recombination is intrinsic to the material, and depends only on the base resistivity. It therefore sets an upper boundary for the theoretical effective lifetime of silicon. Shockley-Read-Hall recombination, on the other hand, occurs via defects levels in the band gap, and depends therefore on the material quality. It is usually the dominant bulk recombination source in solar cells.

The surface of a silicon wafer can be regarded as a large imperfection in the crystal, and it represents a continum of defects in the band gap. If the surface recombination rate is low and equal on each side, $\tau_{surface}$ can be approximated by:

$$\frac{1}{\tau_{surface}} = \frac{2S_{eff}}{W} \cdots\cdots\cdots (5)$$

where W is the wafer thickness and S_{eff} is the surface recombination velocity. In silicon solar cells recombination in the emitter is also usually significant. It is therefore common to add the emitter recombination rate, $1/\tau_e$, to the other bulk recombination mechanisms in the expression for the effective recombination lifetime (see Equation (4)). Under the assumptions that the emitter is in low injection, and that the depletion approximation is valid, it is possible get an analytical expression for an effective virtual surface recombination velocity that includes both surface and emitter recombination. The emitter, or depletion region, is treated as a virtual surface, and it can be shown that expression for the effective emitter recombination velocity is given as [23][24].

$$S_{eff} = J_{oe}\frac{N_D + \Delta p}{q n_i^2} \cdots\cdots\cdots (6)$$

where J_{oe} is the emitter recombination current, N_D is the base doping density of an n-type wafer, n_i is the intrinsic carrier density, and Δp is the excess / photogenerated carrier density. By inserting equations (5) and (6) into (4) , the total effective recombination lifetime of a silicon wafer with two equal emitters can be expressed as[25][26].

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{aug}} + 2J_{oe}\frac{N_D + \Delta p}{W q n_i^2} \cdots\cdots\cdots (7)$$

Minority Carrier Diffusion Length

The performance of a solar cell is limited by the collection efficiency of the minority carriers. A parameter strongly affecting the collection efficiency is the minority carrier diffusion length (Diffusion length is the average length a carrier moves between generation and recombination) which is related to the minority carrier lifetime by equation:

$$L_n = \sqrt{D_n \tau_n}, L_p = \sqrt{D_P \tau_P} \cdots\cdots\cdots (8)$$

Here L_n, L_p, are the minority carrier diffusion lengths of electrons and holes, respectively. To ensure efficient carrier collection the minority carrier diffusion length should be two to three times the distance between the location of generation and the region where the minority carriers are extracted[27]. The minority carrier diffusion length as a function of lifetime for 20 Ω-cm n-type silicon is illustrated in Figure (3) .

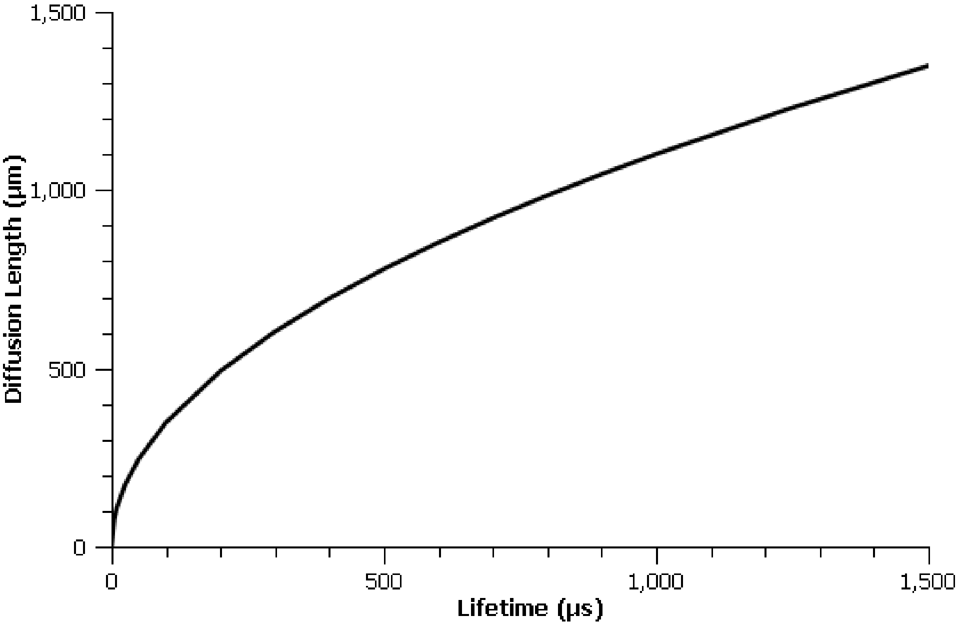

Figure (3): Minority carrier diffusion length as a function of effective lifetime for 20 Ω-cm n-type silicon

The equations used in calculating the solar cell parameters are[28] :

$$I_L = qAG(L_e + W + L_h) \cdots\cdots\cdots (9)$$

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_L}{I_\circ} + 1\right) \cdots\cdots\cdots (10)$$

$$I_{sc} = I_\circ (e^{qV_{oc}/kT} - 1) \cdots\cdots\cdots (11)$$

$$v_{oc} = V_{oc} / (kT / q) \cdots\cdots\cdots (12)$$

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \cdots\cdots\cdots (13)$$

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{I_{sc}.V_{oc}.FF}{P_{in}} \cdots\cdots\cdots (14)$$

3-Results and Discussion

In silicon, the diffusion length is longer for electrons than it is for holes. This is why the thin top region is *n*-type, and the thicker region is *p*-type.

When a solar cell is illuminated, the incoming photons generate hole-electron pairs by collision with valence band electrons. The hole-electron pairs are separated into individual holes and electrons and these individual charge carriers are collected, becoming a photo generated current (I_L). The photo generated current values is obtained from equation (9) where A is the area of the single crystal silicon solar cell and G is the generation rate of electron – hole pairs. Therefore the increase in (L_e) will lead to increase in photo generated current (I_L) as shown in Table (2).

The open circuit voltage indicates a situation in which no current is fed to a load and all of the separated holes and electrons remain in the solar cell until they recombine. This produces a significant voltage across the junction, but no power is delivered to the load. The open circuit voltage for a solar cell is given by equation (10) i.e. the open circuit voltage is proportional to the logarithm of the ratio of photo generated current to dark current. Where $I_\circ$ is the reverse saturation current.

Open circuit voltage of the cell is strongly dependent on the surface recombination velocities, minority carrier diffusion length, device thickness and doping level. Figure (4) show increase in open circuit voltage with increasing diffusion length of electron.

Since in good solar cells the short circuit current (Short circuit current (I_{sc}) (occurs on a point of the curve where the voltage is zero, at this point, the output power of the solar cell is zero)) very quickly nears a saturation value as listed in Table (2).

Short circuit current is strongly affected by bulk and surface recombination of minority carriers in all regions of the device. In addition, short circuit current is affected by the optical properties of the solar cell such as the quality of the anti-reflection coating.

The equation (11) mean the increase in the open circuit voltage lead to increase in the short circuit current as obvious in figure (5) and Table (2).

The normality voltage (v_{oc}) calculated from the equation (12), here The normality voltage is directly proportional with open circuit voltage, this clear in figure (6) and Table (2).

The fill factor is so named because when graphically represented it indicates how much area under neath the I-V characteristic is filled by the rectangle *VI* in relation to the rectangle $V_{oc}\ I_{sc}$.

The fill factor normally lies in the range (0.7- 0.85) for good cells and it is calculate from the equation (13) which show the increase in (v_{oc}) will lead to increase in (FF) as it is shown in figure (7) and Table (2).

The efficiency of photovoltaic energy conversion is very limited for physical reasons. Around 24% of solar radiation has such a long wavelength that it is not absorbed. A further 33% is lost as heat , as the excess photon energy (in the short wavelength region) is converted into heat. Further losses of approximately (15-20)% occur because the cell voltage only reaches around 70% of the value which corresponds to the energy gap.

The efficiency of a solar cell is defined as the ratio of the photovoltaically generated electric output of the cell to the luminous power falling on it as shown in equation (14).

Figure (8) and Table (2) reveals increase in the efficiency with increasing the previous parameters.

When using electronic calculator programme in visual basic language and input the constants and variables (Table 1) in addition to the equations (9,10,11,12,13,14) of the parameters which we would calculate it and run the programme we obtain the results (Table 2).

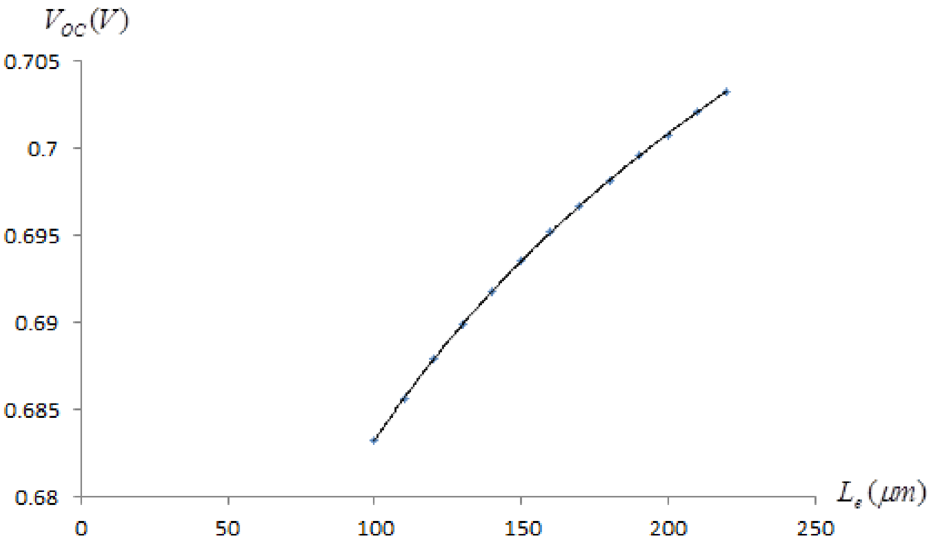

Figure (4) The diffusion length versus open circuit voltage.

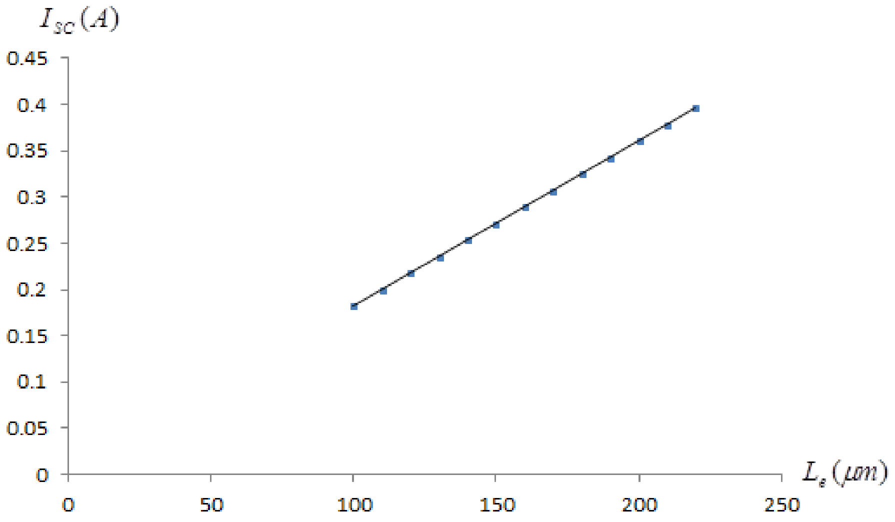

Figure (5) The diffusion length versus short circuit current.

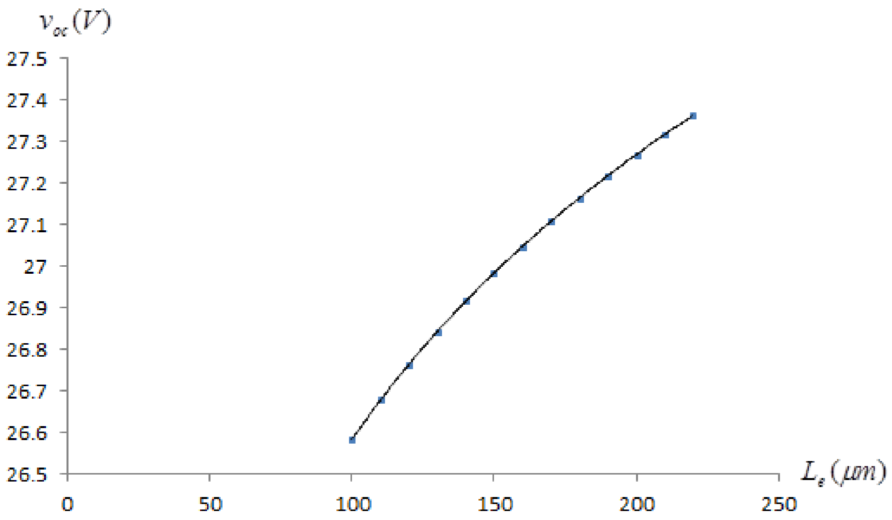

Figure (6) The diffusion length versus normality voltage.

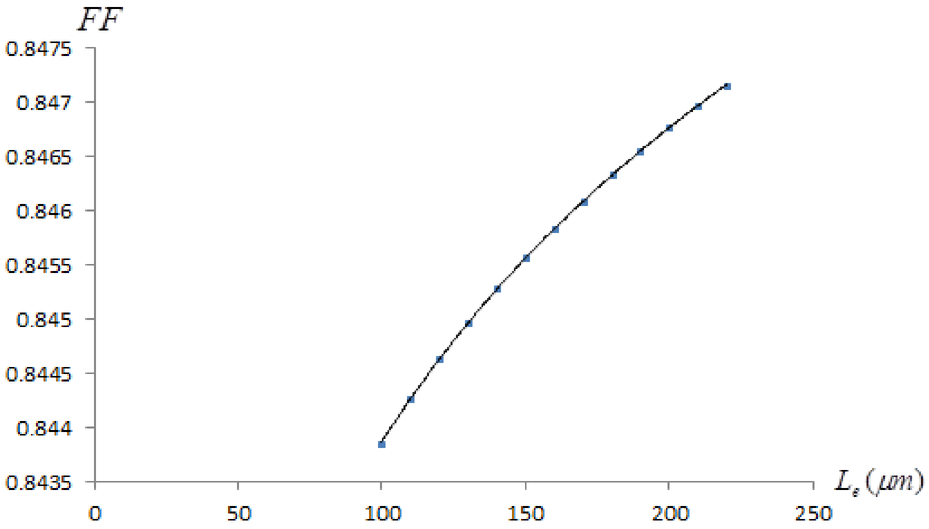

Figure (7) The diffusion length versus fill factor.

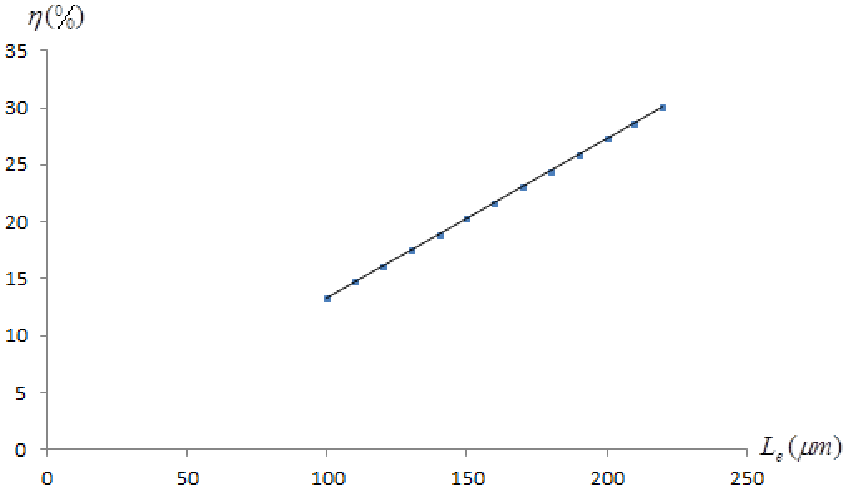

Figure (8) The diffusion length versus efficiency.

Table (1) show the constants and variables used in electronic calculator programme in visual basic language (data are presented for solar cell made from silicon) .

Constants		
Quantity	**Symbol**	**Value**
Boltzmann's constant	k	$1.38\times10^{-23}\,JK^{-1}$
absolute temperature	T	$298K$
Electronic charge	q	$1.6\times10^{-19}\,Amp.\sec$
Acceptor concentration	N_a	$2\times10^{16}\,cm^{-3}$
Donor concentration	N_d	$10^{19}\,cm^{-3}$
Depletion layer width	W	$0.01080512647\times10^{-4}\,cm$
Built-in voltage	$V_\circ$	$0.886448291\,Volt$
Intrinsic carrier concentration	n_i	$1.45\times10^{10}\,cm^{-3}$
Permittivity of a medium	ε_s	$105.36498\times10^{-14}\,Farad/cm$
Solar cell area	A	$78.5cm^2$
Generation rate of electron – hole pairs	G	$1.423026646\times10^{20}\,cm^3.\sec^{-1}$
Hole diffusion length	L_h	$1.7\times10^{-4}\,cm$
Saturation dark current	$I_\circ$	$5.177470261\times10^{-13}\,Amp/cm^2$
Variables		
Electron diffusion length	L_e	$(100-220)\times10^{-4}\,cm$

Table (2) show the results obtained by run the electronic calculator programme in visual basic language

$L_e(\mu m)$	$I_L(A)$	$V_{OC}(V)$	$I_{SC}(A)$	$v_{oc}(V)$	FF	$\eta(\%)$
100	0.181789905	0.683285181	0.181789901	26.58438599	0.843859227	13.35279255
110	0.199663120	0.685695559	0.199663120	26.6781659	0.844264389	14.72441348
120	0.217536334	0.687899146	0.217536334	26.76390024	0.844632765	16.10107391
130	0.235409549	0.689928638	0.235409549	26.84286112	0.844970341	17.48235995
140	0.253282764	0.69180954	0.253282759	26.91604087	0.845281758	18.86791957
150	0.271155978	0.693562135	0.271155977	26.98422858	0.845570691	20.25745215
160	0.289029193	0.695202815	0.289029192	27.04806206	0.845840097	21.65069512
170	0.306902408	0.696745019	0.306902408	27.10806416	0.846092388	23.04741915
180	0.324775622	0.698199902	0.324775613	27.16466891	0.846329561	24.4474208
190	0.342648837	0.699576826	0.342648836	27.21824049	0.846553282	25.85052201
200	0.360522052	0.700883721	0.360522052	27.26908748	0.846764961	27.25655913
210	0.3783952669	0.702127367	0.378395259	27.31747367	0.846965798	28.66538663
220	0.396268481	0.703313605	0.396268472	27.36362632	0.847156824	30.07687395

4-Conclusions

The minority carrier lifetime and the diffusion length depend strongly on the type and magnitude of recombination processes in the semiconductor. For many types of silicon solar cells, SRH recombination is the dominant recombination mechanism. The recombination rate will depend on the number of defects present in the material, so that as doping the semiconductor increases the defects in the solar cell, doping will also increase the rate of SRH recombination. In addition, since Auger recombination is more likely in heavily doped and excited material, the recombination process is itself enhanced as the doping increases. The method used to fabricate the semiconductor wafer and the processing also have a major impact on the diffusion length. From the results, we conclude that:

1-Semiconductor materials that are heavily doped have greater recombination rates and consequently, have shorter diffusion lengths.

2-Higher diffusion lengths are indicative of materials with longer lifetimes, and is therefore an important quality to consider with semiconductor materials.

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الخلاصة

يتضمن البحث دراسة نظرية لتأثير أطوال انتشار مختلفة للإلكترون على معلمات خلية شمسية سليكونية أحادية البلورة.

استعملت قيم مختلفة لطول الانتشار للإلكترون وبواسطة استعمال برنامج الحاسبة الالكترونية بلغة فيجال بيسك. النتائج توضح تزايد معلمات خلية شمسية سليكونية أحادية البلورة مع تزايد طول الانتشار للإلكترون وبالتالي حساب الكفاءة النظرية للخلية والتي تراوحت بين % (13.352 - 30.076).

وقد تم رسم العلاقة بين قيم طول الانتشار للإلكترون والمعاملات الداخلة في حساب كفاءة الخلية ومن ثم رسم العلاقة بين أطوال الانتشار هذه والكفاءة النظرية لهذه الخلية إضافةً إلى ملاحظة تأثير العوامل الأخرى على تلك الكفاءة وتم التوصل من ذلك إلى الملاحظات والاستنتاجات المهمة والتي يمكن تلخيصها في ميزتين:

أولاً : تحسين أطوال الانتشار في كل من السطح الأمامي والخلفي سوف يقلل الخسائر بسبب إعادة الاتحاد عند السطح الأمامي والخلفي ويجعل التيارات الضوئية أقرب إلى القيم المثالية.

ثانياً : استعمال طبقة قاعدة ذات سمك أقل من طول الانتشار للحاملات الأقلية ، والتي تحسن كفاءة التجميع للخلية الشمسية .

الكلمات المفتاحية: الخلية الشمسية، السليكون، البلورية، طول الانتشار، الكفاءة.