

THEORETICAL STUDY OF INFLUENCE OF SOME MATERIAL PARAMETERS ON SOLAR CELL EFFICIENCY

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ABSTRACT

Silicon solar cells are prevailing types in the commercial market due to their stability, robustness and reliability. In this article, we explored the important controllable design parameters affecting the performance of the silicon p-n junction solar cells by using the computer program (Matlab scrip file). Through the simulation process we also determined the sensitivities of each parameter. Besides that, some hypothetical materials are also examined to explore the effect of band gap, doping process and thickness of n-layer. We have come out the optimum parameters to achieve the best performance of this type of cell. A simple one-diode model is used in order to predict how the performance Silicon solar cell changes its characteristics with doping process. It was found that the optimum doping concentration of the base from (10^{16} - 10^{19}) cm^{-3} and optimal thickness of n-layer is about (10-100) μm for silicon solar cell.

KEYWORDS: Energy band, Doping process, Optimum parameter, Photovoltaic module.

I. INTRODUCTION

Solar energy is one of the most effective, less expensive, harmless and less environmental pollution effect of renewable energy sources. The utilization of solar energy can be categorized in two ways: solar heating/cooling and solar electricity. This energy can be converted into electrical energy through implementation of photovoltaic array. Recently, photovoltaic (PV) systems application is well recognized and widely used in electric power technologies [Mellit et al., 2007]. Researchers have predicted and noted the lifetime stability of phosphorous-doped Czochralski silicon wafers and solar cells made on them in contrast with their boron-doped counterparts [Schmidt et al., 1997- Glunz et al., 1999]. J.E.Cotter, suggests that n-type silicon wafers are better suited for high-efficiency commercial silicon solar cells [Cotter et al., 2006]. It has been found that low base doping concentrations are essential for minimizing the effective rear surface recombination velocity of the back surface field [Reichel et al., 2011]. A higher open-circuit voltage could be obtained from the compensated solar cells due to its larger net doping concentration [Chengquan et al., 2012]. With the help of the PC1D simulation program, it was expected that the elimination of the boron depletion layer due to the presence of silicon nitride layer will be beneficial for the higher cell conversion efficiency [Su-won and Young, 2010]. Julio, it has been shown that the emitter of passivity emitter solar cells must be moderately doped, with optimum values near

($N_D \approx 10^{19} \text{cm}^{-3}$) [Julio et al., 1991]. Experimental results which have shown highly efficient cells with thick emitters (2 μm). Our results indicate this kind of cells may achieve high efficiencies, whenever the surface dopant concentration is low ($N_D = 10^{19} \text{cm}^{-3}$), and in addition the surface is well passivated [Arturo, 1991]. A. Cuevas, [Cuevas et al., 1994], noted that the front surface recombination velocity (S_F) increases rapidly with increasing surface concentration of the phosphorus doping. One of important parameter that determines the design and performance of solar cells are concentrations of dopant atoms and band gapetc.

II. SIMULATION USING (MATLAB SCRIP FILE)

For one successful simulation, input parameters include: the thickness of p-type or n-type material, the doping density, band gap, electron affinity, effective conduction and valence band density, the absorption coefficient for the sun light spectra, dopant and acceptor energy levels, temperature, motilities of electrons and holes [Carig and Carbon, 2008].

III. J-V CHARACTERISTICS FOR P-N JUNCTION SOLAR CELL

The ideal equation that represents (J-V) characteristics of p-n junction solar cell is characterized by [Carig and Carbon, 2008].

$$J = J_L - J_s (e^{qV/nkT} - 1) \dots \dots \dots (1)$$

J_L : photocurrent density

J_s : saturation current density (A.cm^{-2})

q : The electron charge= 1.602×10^{-19} (C);
 T : PV module temperature(K)
 n : Ideality factor of the PV module
 k : Boltzmann's constant = 1.380×10^{-23} (J.K⁻¹)

Where J_s is given by;

$$J_s = qn_i^2 \left[\frac{D_n}{L_n N_a} + \frac{D_p}{L_p N_D} \right] \dots\dots\dots(2)$$

The relation between (J_s) and (E_g) is given by;

$$J_s \approx EXP \left\{ \frac{-E_g}{KT} \right\} \dots\dots\dots(3)$$

Where;

D_n, D_p : are the diffusion coefficient of electrons and holes (cm²:s⁻¹);
 n_i : intrinsic carrier concentration (cm⁻³);
 L_n and L_p : are the diffusion length of electrons and holes (cm);
 E_g : is the band gap energy.
 N_D, N_a : are the doping density of n-region and p-region(cm⁻³).

Short circuit current I_{sc} : When $V=0$, the current is the short circuit current J_{sc} . From equation (1), we can get:

$$J_{sc} = J_L \dots\dots\dots(4)$$

In general, J_L is strongly dependent on the illumination conditions, absorption and transport properties of each region. J_L generated by and proportional to the amount of light absorbed by the PV. J_L is calculated by;

$$J_L = q \int_0^w G_x \eta_c(x) dx \quad (A.m^{-2}) \dots\dots\dots(5)$$

Where

W : width of the device (m)
 G_x : generation rate (m⁻³:s⁻¹)
 $\eta_c(x)$: collection efficiency.

As (J_L) is generated, a voltage (V) appears across the terminals and as (V) forward biases the equivalent diode of the pn junction, current density (J_{Diode}) increases and flows in the opposing direction to (J_L). The equation for this current density through the biased equivalent diode J_{Diode} is then [Carig and Carbon, 2008];

$$J_{Diode} = J_s (e^{qV/nkT} - 1) \dots\dots\dots(6) \quad (A.m^{-2})$$

The net current density can be written;

$$J = J_L - J_{Diode} \dots\dots\dots(7)$$

So, using equations (Chengquan et al., 2012) and (7) net current density J can be written:

$$J = J_L - J_s (e^{qV/nkT} - 1) \dots\dots\dots(8)$$

Power density can be calculated by the product:

$$power \ density = JV \ (W.m^{-2}) \dots\dots\dots(9)$$

Open circuit voltage: When $J=0$, V is the open circuit voltage, which is the maximum voltage available for given conditions. From equation (8) set $J=0$:

$$V_{oc} = \frac{n k T}{q} \ln \left(\frac{J_L}{J_s} + 1 \right) \dots\dots\dots(10)$$

Fill factor is a standard PV ratio and is mainly a measure of the quality of the pn junction. Fill factor in simple terms is the ratio of the area of the purple actual maximum power density rectangle over the orange ideal maximum power density rectangle. The Fill factor of the PV is calculated using the equation:

$$FF = \frac{power \ density_{max}}{V_{oc} J_{sc}} \dots\dots\dots(11)$$

The efficiency η of the PV is a follow on from the Fill factor, also using the maximum point of power density and is calculated using the equation:

$$\eta = \frac{power \ density_{max}}{input} \% \dots\dots\dots(12)$$

Where $power \ density_{max}$ = maximum point of power density (mW.cm⁻²)

Input The National Renewable Energy Laboratory (NREL)(air mass 1.5)AM1.5 sun (assumed)=1kW.m⁻²
 = 100mW.cm⁻²[American Society for Testing and Materials, 2003].

Also, the effect of doping on internal quantum efficiency is studied theoretically. Internal quantum efficiency (IQE) is due to photons incident on surface and given as[American Society for Testing and Materials, 2003]:

$$IQE = \frac{EQE}{1 - R(\lambda) - T(\lambda)} \dots\dots\dots(13)$$

Were,

$R(\lambda)$ is the reflectivity of the Si,
 $T(\lambda)$ is the transitivity of the Si.

EQE is external quantum efficiency is the current generated due to the photon absorption at the surface.

Base collection efficiency is relatively straight forward in comparison to emitter collection efficiency and is given by the equation [Kittidachachan et al., 2007];

$$\eta_c(x) = \cosh \frac{x}{L_n} \left\{ \frac{\tanh \frac{wb}{L_n} + \frac{SbLn}{Dn}}{1 + \frac{SbLn}{Dn} \cdot \tanh \frac{Wb}{L_n}} \right\} \cdot \sinh \frac{X}{L_n} \dots\dots\dots(14)$$

Where:

x =distance from the pn junction (cm);
 W_b = width of the base (cm);
 L_n =electron diffusion length (cm);
 S_b =back surface recombination velocity (cm.s⁻¹);
 D_n = electron diffusivity (cm².s⁻¹);

IV. RESULTS AND DISCUSSION

a. Doping Density

Table (1) represents the major input parameters for crystalline silicon p-n junction solar cell that was used in this study. Table (2) show that when (N_a) is increased from the range of (10^{16} - 10^{20})(cm⁻³). It's clear at high doping short circuit current (J_{sc}) decreases while the open circuit voltage (Voc) slightly increases. As result, the efficiency decreasing with high doping. The dependence relationship on doping density can be explained well by the ideal p-n junction (J-V) relationship. The increment of (N_a) would decrease the life time and thus the diffusion length of minor carriers generated by increase density of recombination centers. In this way, the photocurrent density is reduced hence results a smaller short circuit current. For the open circuit voltage, from equation (2), increasing, (N_a) leads to a smaller saturation current (J_s). (Voc) increases as predicted by equation (10) though (J_L) decreases. Finally, efficiency increases as the doping density increases as the balanced results of (J_{sc} , Voc and FF) as shows Table (2) for P-doping . However, the increment is not significant when the doping density is high enough ($\sim 10^{20}$ cm⁻³). In higher doping, the efficiency decrease due to increasing the recombination of charge carriers. The optimum doping concentration is found to be N_a (10^{16} - 10^{19}) cm⁻³. Fig.(1) shows the (J-V) characteristics under illumination at different

levels p-doping for (n) doping the result are similar. One can see that doping results in substantial decreasing of the short- circuit current density (J_{sc}).The open-circuit voltage (Voc) slightly increases. As a result, the efficiency decreasing with high doping. The Internal quantum efficiency is calculated for different concentration of doing (N_a).In fig.(2) As can be seen from the plot, The Internal quantum efficiency decreases in the long wave rang at increases in concentration of doping because of reduction in (EQE) .Highly doped causes higher recombination center, decrease (IQE) because of the Auger recombination inside the highly doped region and surface recombination velocity. Auger recombination is most important in heavily doped materials [Tyagil et al., 1983].Figure (3), shows the results of the base collection efficiency for different back surface recombination velocity (S_b). The results are similar for front surface recombination velocity (S_F) .The collection efficiency of the base was studied analytically. The collection efficiency calculated from equation (14) for different values of the back surface recombination velocity is shown in Fig. (3) The plot also suggests that collection efficiency depends strongly on the surface recombination velocity and the same result obtained from [Kittidachachan et al., 2007].As can be seen from the plot; the collection efficiency increases towards the junction boundary and is highest at the junction edge. The collection Efficiency at the back surface decreases from (0.74 to 0.41)as (S_b) increases from (100 to 500) cm. s⁻¹.These results are in a good agreement with results of [Kittidachachan et al., 2007].

Table (1): Major input parameters for crystalline silicon p-n junction solar cell.

Parameter	Values
Relative permittivity (ϵ_r)	11.9
Mobility μ_e, μ_p (cm ² .V ⁻¹ .S ⁻¹)	$\mu_e=1350, \mu_p=450$
Doping density N_a, N_D (cm ⁻³)	$N_a=(10^{16}-10^{20}), N_D=(10^{16}-10^{20})$
Band gap E_g (eV)	1.12
Affinity (χ),(eV)	4.05
Effective density N_c, N_v (cm ⁻³)	$N_c=2.80 \times 10^{19}, N_v=1.04 \times 10^{19}$
Temperature T(K)	300

Table (2): The summarized results obtained by changing the doping density at p-type silicon. Fixed parameters include $T=300K$, P.thickness= n.thickness= 1000nm, $N_D N_P=10^{16}cm^{-3}$

$N_a (cm^{-3})$	$J_{sc}(mA/cm^2)$	$Voc(volt)$	FF	η
10^{16}	9.8319	0.8440	0.8371	6.9472
10^{17}	9.8314	0.8591	0.8392	7.0884
10^{18}	9.8296	0.8643	0.8400	7.1361
10^{19}	9.7780	0.8650	0.8401	7.1054
10^{20}	8.2195	0.8593	0.8393	5.9278

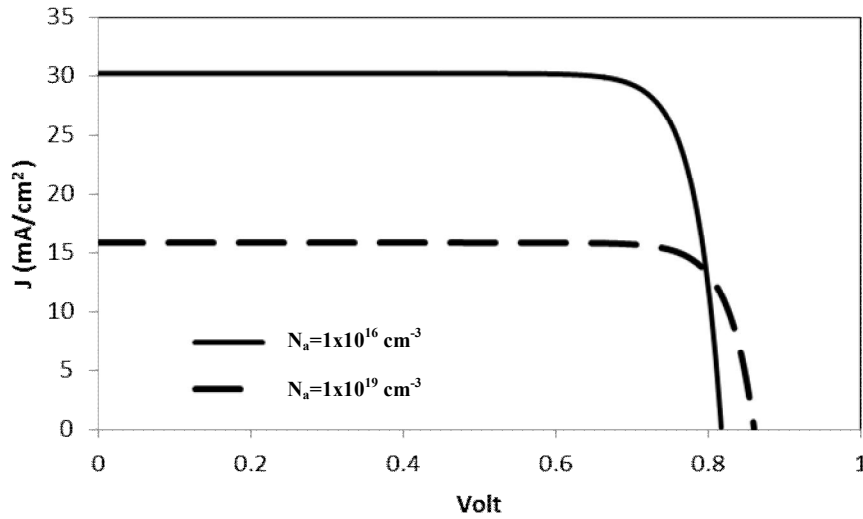


Fig.(1): J-V characteristics at different acceptor dopant concentration.

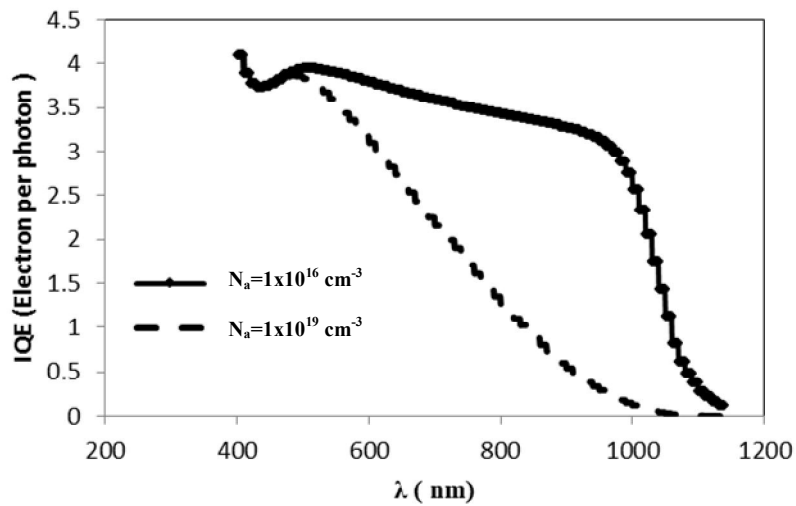


Fig.(2): IQE Vs wavelength of light at different acceptor dopant concentration.

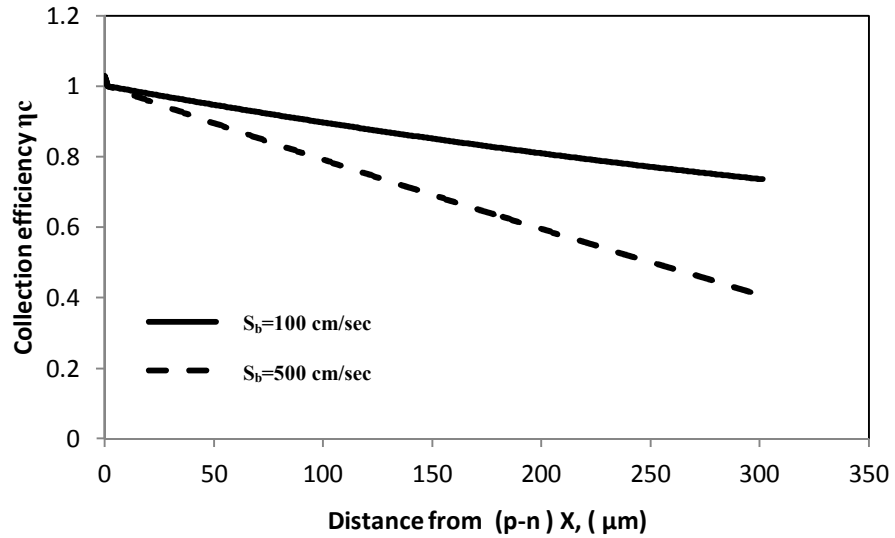


Fig.3: Matlab Model of collection Efficiency within the base as a function of distance from p-n junction at different Sb.

b. Thickness

In order to find out the best parameters of this silicon solar cell, we calculate the thickness of n-silicon layer and display its effects on this cell. From table (3) it is easy to conclude that the n-silicon layer should be thick enough to absorb light .If the layer is thin, the sun light cannot be

absorbed well, leading to a low efficiency. On the other hand, this layer can't be too thick. If it's too thick, the carriers can't arrive at the front contact owing to recombination. The best thickness of the n-layer, the best thickness of the n- silicon layer is the value of (10- 100) μm.

Table (3): Simulation results of effect of varying n-layer thickness. Fixed parameters $N_D = N_A = 10^{16} \text{cm}^{-3}$, p-layer= 10nm.

n-thickness(μm)	η%
0.01	0.248
0.1	0.936
1	4.827
10	19.844
40	22.820
80	23.840
100	24.820
110	5.220
200	0

c. Band gap

From Table (4), the bang gap of p-X can be tuned while other properties retained. Fixing parameters: T=300K. p-layer thickness=n-layer=1000nm, and the band gap of p-Si is 1.12 eV. Assumption: There exists a hypothetical material with other parameters same as Si expect E_g . The general feature is that the open circuit voltage increases while the short circuit current decreases except for very small band gap

(0.5eV). The increment of V_{oc} can be explained by equation (8) and (10), larger E_g leads to smaller (reverse saturation current) I_s and thus results a larger V_{oc} . While the decreasing of J_{sc} is due to that, smaller amount of photons have enough energy to generate electron-hole pairs. These two factors compete with each other to determine the changing of efficiency. The optimal material which has band gap from (1- 1.8) eV.

Table (4): The solar cell performance parameters with structure n+-Si-p-X (X stands for an unknown material).

Eg(eV)	$\eta\%$	FF	Jsc	Voc
0.5	2.74	0.781	7.346	0.478
1.12	6.27	0.8257	9.884	0.769
1.5	6.01	0.8255	9.494	0.767
1.8	5.02	0.8245	8.003	0.762
2	4.11	0.8235	6.608	0.755
2.5	1.92	0.8193	3.216	0.731

V.CONCLUSIONS

Intrinsic material properties including band gap, electron affinity, doping profile, geometric construction are import factors influencing the solar cell performance. The numerical simulation is an efficient approach to select the optimum value for the best performance. A very important from point of view of the solar cell

designing and processes is that the performance of the cell is practically in sensitive to the surface concentration. The present model is designed specifically to predict the cell efficiency. Finally the preceding results and conclusions show that the model proposed in this paper is useful tool for designing optimum parameters.

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الخلاصة

الخلايا الشمسية السيليكونية تستعمل بشكل تجارى واسع بسبب استقراريتها والمتانة والموثوقية. في هذا البحث تم دراسة التحكم في اهم بارامترات تصميم الخلايا التي تؤثر على اداء الخلايا الشمسية السيليكونية ذات المفرق (p-n) باستخدام برنامج حاسوبي (ملف ماتلاب). من خلال عملية المحاكاة تم تحديد حساسية البارامترات. إضافة الى ذلك، تم دراسة بعض المواد الافتراضية لبيان تأثير كل من الفجوة المحظورة، عملية التشويب و سمك الطبقة (n). تم الحصول على البارامترات الامثل لتحقيق افضل أداء لهذا النوع من الخلايا الشمسية. تم استخدام نموذج داوود أحادي بسيط لتخمين تغير أداء الخلايا الشمسية السيليكونية مع تغير عملية التشويب. وجد أن تراكيز الشوائب الأمثل لطبقة للقاعدة من $(10^{16}-10^{19} \text{ cm}^{-3})$ والسمك الامثل لطبقة (n) حوالي (10-100) ميكرون لخلية السيليكون الشمسية.

پوختنه

له بهر جیگری، توکمه یی و دلنیا یی له کار کردنی خانه کانی سلیکونی کارو روناکی به شیوه یه کی بهر فراوان به کار ده هیتریت. مه به ست له م لیکۆلینه وه یه، دیاری کردنی ههستیاری گرنگترین پارامتره کانی په یوه نیدی دار به دروست کردنی ئەم خانانیه (داوودی P-N) به بکاره یانی پروگرامی مه تله ب (Matlab). ههروه ها لیکۆلینه وه کرا له سه ر پارامتره کانی بۆشایی و وزه ی ریگه پینه دراو (Energy Gap) و زیاد کرنی خلته (Doping Effect) و ئەستووری چینی (n) بۆ ده ست خستنی باشترین کارایی ئەم خانانه. نرخه ی چری مادده ی خلته $(10^{16}-10^{19} \text{ cm}^{-3})$ و ئەستووری چینی (n) $(10-100 \mu\text{m})$ به باشترین دیاری کرا.