Theoretical Study of the effect of impurity concentrations on the efficiency of the single crystal silicon solar cell

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Abstract

Effect of different impurity concentrations that is added during the single crystal silicon solar cell manufacturing on the efficiency of cell has been studied and calculating the theoretical efficiency of the cell (by using the electronic computer programme in visual basic language), which varied between (0.007-3.827) % .

The relationship between the impurity concentration and the input parameters in calculating the cell efficiency has been plotted and then plotted the relationship between these concentrations 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 .

دراسة نظرية لتأثير تركيز الشوائب على كفاءة الخلية الشمسية السليكونية الأحادية البلورة

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الخلاصة :

لقد تم دراسة تأثير تراكيز مختلفة من الشوائب المضافة خلال تصنيع الخلية الشمسية السليكونية الأحادية البلورة على كفاءة تلك الخلية وحساب الكفاءة النظرية لها (باستخدام برنامج الحاسبة الالكترونية بلغة فيجوال بيسك) والتي تراوحت بين % (0.007-3.827) .

وقد تم رسم العلاقة بين تركيز الشوائب والبارامترات الداخلة في حساب كفاءة الخلية ومن ثم رسم العلاقة بين هذه التراكيز والكفاءة النظرية لهذه الخلية إضافةً إلى ملاحظة تأثير العوامل الأخرى على تلك الكفاءة وتم التوصل من ذلك إلى الملاحظات والاستنتاجات المهمة .

Introduction

Due to high price of fossil energy source and huge pollution of environmental issue in recent years , the development of renewable energy regains our attention . The development of the solar energy industry is one of the most popular technologies in renewable energy. For the solar energy becoming a practical renewable energy, it is widely accepted that we must have efficient ways to convert radiation into electricity as called photovoltaic (PV) effect . Nowadays , however , the unit price of converting power by solar energy is much higher than that of the traditional energy source . Thus , how to enhance the over all efficiency and reduce the manufacturing cost in an important subject for developing the solar energy industry [1,2].

It is well known that cost reductions of the developed solar cell can be achieved either by a reduction of manufacturing cost or by an increase in solar cell efficiency and defects in the bulk of Si to remove the band – gap levels into the valence or conduction bands [3-6].

Among the types of Si – based crystalline,singlecrystalline , polycrystalline , and amorphous , the polycrystalline Si wafer owns the highest growth rate and the lowest fabrication cost [7,8].Unfortunately , the polycrystalline Si contains a large number of defects and dislocation suffered from lattice mismatch , thus yielding to the least conversion efficiency on the PV applications [8].Then , to improve the conversion efficiency of polycrystalline Si , they are important to understand the roles of these impurities and defects and then reduce these amounts .

In this paper the effect of different impurities concentration on the parameters (V_o , W L_e , L_L , V_{oc} , I_{sc} , v_{oc} , FF) and on the efficiency (η) of the single crystal silicon solar cell have been studied .

Theory

Silicon solar cells are made using either single crystal wafers , polycrystalline wafers or thin films .

Single crystal wafers are sliced , (approximately 1/3 to 1/2 of a millimeter thick) , from a large single crystal ingot which has been grown at around $1400^{\circ}C$, which is a very expensive process and have attained an efficiency of 24.7 % . The silicon must be of a very high purity and have a near perfect crystal structure . Polycrystalline wafers are made by a casting process in which molten silicon is poured into a mould and allowed to cool , then sliced into wafers . This process results in cells that are significantly cheaper to produce than single crystal cells , but whose efficiency is limited to less than 20 % due to imperfections in the crystal structure resulting from the casting process. Amorphous silicon is one of the thin film technologies , is made by depositing silicon onto a glass substrate from a reactive gas such as silane (SiH_4) . Since amorphous silicon cells have no crystal structure at all , their efficiencies are presently only about 10 % due to significant internal energy losses [9] .

A solar cell is a device that directly converts light into electricity . The incident light consists of photons with energy $E_{ph} = hc/\lambda$. In the absorption process , the energy of the photon transforms an electron from its valence state to a conduction state [10,11].This process is called the excitation of an electron from the valence band (VB) to the conduction band (CB). In such a transition, both energy and momentum have to be conserved . This process is also called electron/hole generation process. The absorption of a photon depends on the photon wavelength and on the material itself .The energy of the photon has to be enough for the electron transition from the VB to the CB. Therefore, it has to be larger than the band gap of the semiconductor E_g. The absorption of light and generation of electron / hole (*e/h*) pairs is not enough to generate electricity. The separation of the *e/h* pairs from each other and the collection of them from different electrodes before they recombine again is necessary for the generation of electrical power. The average time, in which the charge carriers live before they recombine is called the carrier lifetime τ . The minority charge carriers diffuse in a semiconductor due to the concentration gradient for a distance in a duration equals its lifetime before they recombine . This distance is defined as the minority carrier diffusion length $L_{n,p} = \sqrt{D_{n,p}\tau}$ .For electrons in p-type semiconductor and holes in n-type semiconductor respectively, with the minority carrier diffusion constant $D_{n,p}$ in p-type and n-type semiconductors. The carriers recombine more likely at the surfaces of the semiconductor , the interfaces with metals, and defects like grain boundaries . The recombination at the surface is characterized by the surface recombination velocity *S*. Therefore, the effective diffusion length L_{eff} depends on the diffusion length $L_{n,p}$ and the surface recombination velocity *S* [10,12] . The process of substituting boron or phosphorous atoms for silicon atoms is called doping .This is often done by thermal diffusion [13] .

Recombination losses :

Occurs in the volume of the solar cells . Carriers generated get recombine with each other in order to maintain equilibrium condition . Areas were these losses occur in large magnitude are Bulk region (base region),Top surface,Metal to semiconductor contact areas, Junction region [14].

Photon incident on the solar cell generates electron hole pairs , these generated pairs are called as carriers. Generated carriers needs to be separated before they recombine, with emission of energy. Recombination causes loss of carrier and affects the performance of the cell. Recombination of carriers generated in the Solar cells due to photo excitation is one of the most dominating loss occurring in the solar cell .

Bulk recombination : To obtain good cell performance, recombination throughout the cell has to be kept to a minimum. Recombination in bulk regions can be minimized by choosing as high a quality starting material as possible. Material quality is generally characterized by a minority carrier lifetime, τ **.**The lower the dopant concentration in the substrate, generally the higher this lifetime will be. This is offset by a compensating effect of doping upon recombination rates. This compensation is due to the fact that the higher the dopant density, the lower the minority carrier concentration for any given voltage across the cell. The recombination rate is determined by the product of this concentration and the inverse of the carrier lifetime. For ideal silicon material, low dopant density is undoubtedly the best choice to minimize this product[15]For actual material , several other issues are involved and the optimum dopant density depends upon the particulars of cell design . Obviously, the thinner the bulk region, the lower the bulk recombination will be .

a-Band to band recombination :

It is a radiative form of recombination in which an electron from conduction band combines with the hole in the valence band with emission of energy (light) Figure(1) band to band recombination occurs in direct band gap semiconductors .

b-Trap assisted recombination :

Dominant form of recombination mechanism in most of the solar cells . Due to the impurities present in the semiconductor an additional energy level Et is introduced within the forbidden energy gap Figure(1).This energy level acts as a trap and captures electrons and holes, leading to recombination. Trap assisted recombination is a two step process in which electrons and hole recombine in traps and then fall back into the valence band, completing the recombination process.

c-Auger recombination : Solar cells when exposed to high intensity of photons, exhibit the phenomenon of Auger recombination. It involves three particle electron-electron-hole or hole-hole-electron .When hole from the valence band gets recombine with the electron in the conduction band the excess energy released during recombination is absorbed by the neighboring electron in the conduction band which then goes to some higher energy level and then again falls back to the conduction band with release of energy Figure (1) [14] ..

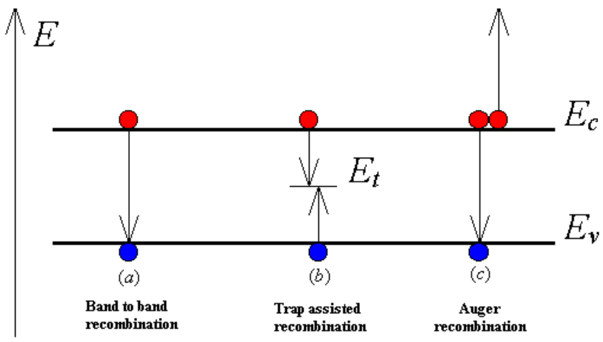

Figure (1): Recombination processes in semiconductors[14] .

Impurities with energies for electrons in the middle of the energy gap were found to greatly enhance recombination , which is detrimental for the efficiency [16].

Surface recombination :

Surface of the solar cells have large number of dangling bonds due to abrupt termination of crystal structure . These dangling bond acts as recombination centers. Carriers generated at the surface fall in to the dangling bond and recombine with the hole [16] .

Properties of transition metal impurities and their effect on silicon solar cell performance :

Metal impurities degrade Si solar cell performance primarily by introducing SRH centers in the band gap that reduce the minority carrier diffusion length in the base. Transition metals are the most detrimental impurities in the silicon solar cells because they can be found in the silicon growth environment, and have energy levels near mid-gap, high diffusivities, and high solubilities. Impurities such as Cr, Mn , Fe, Co, Ni, and Cu are well known as fast diffusers in silicon , and are particularly harmful if found in the material growth environment .The diffusivity for transition metal impurities generally increases with atomic number with Cu having the highest diffusivity. Substitutional impurity diffusion is somewhat retarded in Si and the diffusion coefficient can be $10^{-11}cm^2/s$ even at temperatures near the melting point of Si. Among the metallic impurities that occupy substitutional sites in silicon are Au and Pt . The solubility of transition metals also increases with atomic number .Highly supersaturated and mobile transition metal impurities show a strong tendency for silicide precipitation .An analytical model developed by Davis et al. predicts the threshold concentration for metallic impurities in Czochralski Si , above which solar cell efficiency declines due to carrier lifetime reduction [17] . The results of the model shown in Figure (2) show that some impurities such as Al , Ni , Cu and Ag do not significantly reduce solar cell performance until concentration levels of 10^{15} cm^{-3} are reached . Metal impurities such as Ti and V are more detrimental and concentrations of only 10^{14} cm^{-3} lead to a 50% (relative) reduction in solar cell efficiency. The effect of Ti on solar cells has been studied by Borenstein et al.[18] who found that a Ti concentration of $4x10^{-13}$ in the space charge region reduces solar cell efficiency to 60% of its original value , in good agreement with Figure (2).

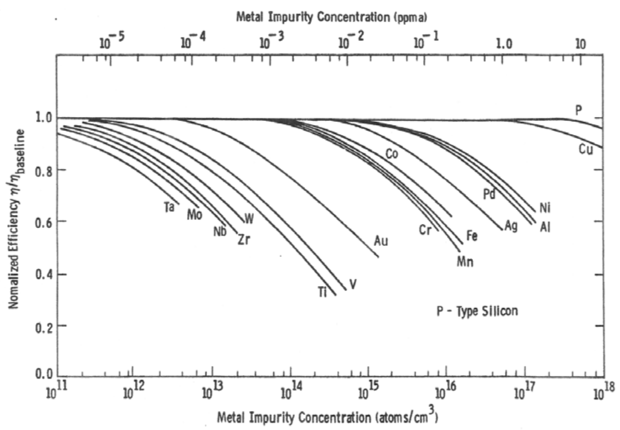

Figure (2) : Effect of various impurity concentrations on single crystal silicon solar cell performance [17].

Efficiency Dependence on Losses

The efficiency of the solar cells(η)is given in terms of the I_{sc}(short circuit current), V_{oc}(open circuit voltage), FF (fill factor) and P_{in} (input power) of the solar cells.

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \cdots\cdots\cdots(1)$$

Equation (1) shows that efficiency depends on I_{sc} , V_{oc} and FF . These factors are solar cell parameter and every solar cell performance is measured with the help of these parameters. Losses and the solar cell parameters are closely linked with the performance of the cell [10].

Results and Discussion

The depletion region width (W) depends on the density of impurity concentrations(N_d) in the semiconductor and being larger when the concentration is less[19] as shown in figure (4) and table (2).

Increasing impurity concentration leads to reducing each of the mobility, diffusion length and lifetime of the carriers[20] as shown in figure (5) and table (2).

The carriers generated near depletion region are separated out very quickly as they get swept away by the electric field present in the depletion region .Were as the carriers which are generated away from the depletion region that is in the bulk region , on the surface , or at the back surface have less probability of getting separated . These carriers will be lost and would not contribute to the current flow if they recombine [14].

Open circuit voltage (Voc) of the cell is affected by recombination of carriers. As recombination increases the(Voc) reduces[14]. The decrease in the open circuit voltage , which is due to the increase in recombination in the solar cell . This recombination increase more drastically when the concentration of the defects is around the base layer doping(~10^{17}cm^{-3}) [21] as shown in figure (6) and table (2). Increasing impurity concentration leads to reducing each of the mobility, diffusion length and lifetime of the carriers and reducing (I_{sc})[20] as shown in figure (7) and table (2).

Extended defects and metallic impurities degrade the solar – cell efficiencies via degradation of the Si minority-carrier lifetimes or diffusion lengths as shown in figure (10) and table (2). Even clean dislocations contain recombination sites Such sites are few .e.g., probably only at kinks and jogs[22].

Typical values for (η) are in the range (12-14)% for a single crystal silicon solar cell.

When using electronic computer programme in visual basic language and input the equations , constants and variables (table 1) and run the programme we obtain the results (table 2) .

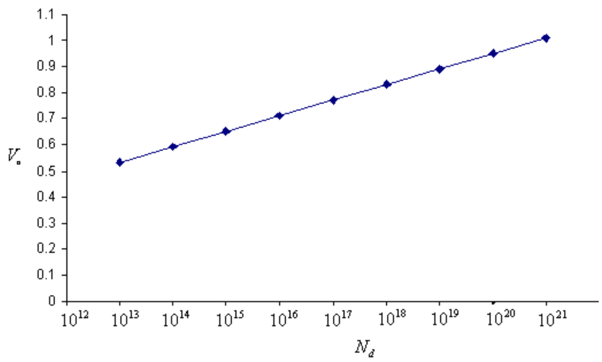

Figure (3) The applied voltage versus impurity concentrations.

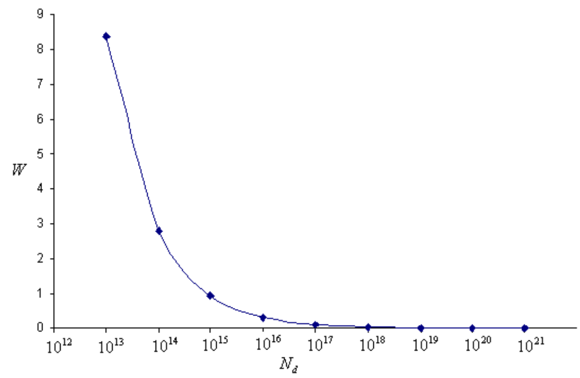

Figure (4) The depletion region width versus impurity concentrations .

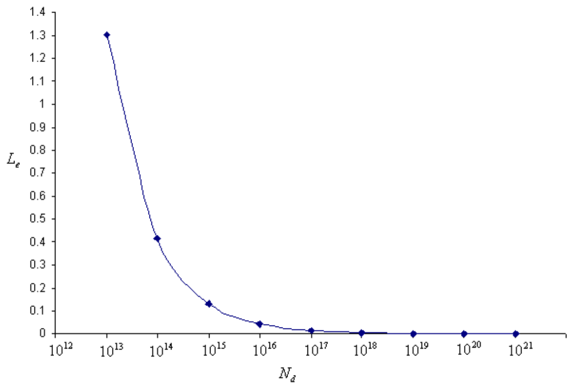

Figure (5) The minority carrier diffusion length versus impurity concentrations .

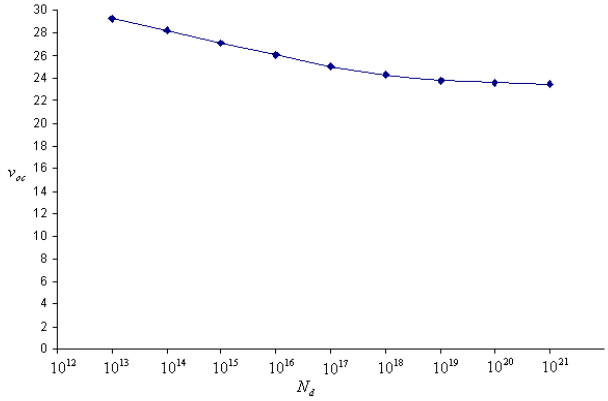

Figure (8) The normality voltage versus impurity concentrations .

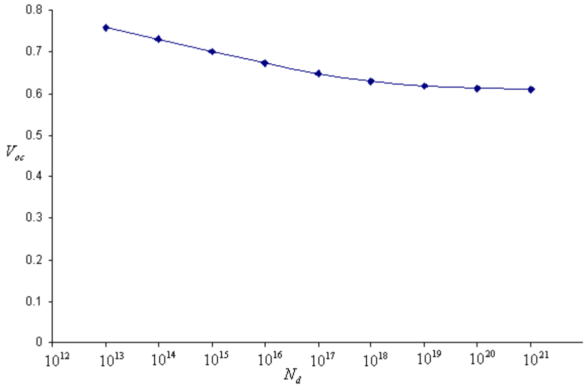

Figure (6) The open circuit voltage versus impurity concentrations .

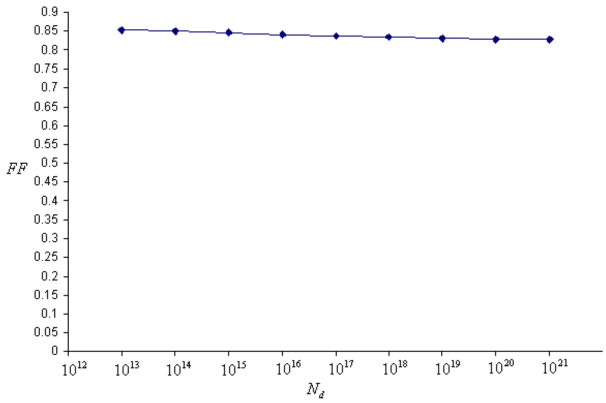

Figure (9) The fill factor versus impurity concentrations .

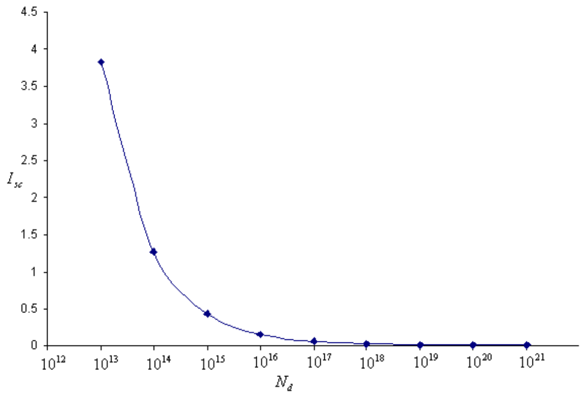

Figure (7) The short circuit current versus impurity concentrations .

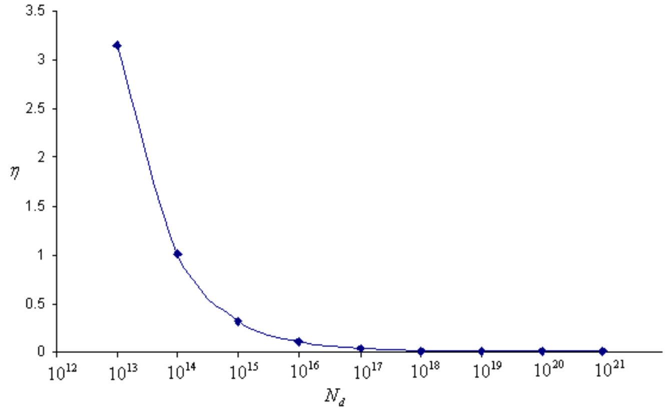

Figure (10) The efficiency versus impurity concentrations .

table (1) show the Equations , constants and variables used in electronic computer programme in visual basic language .

Equations :

$$V_{\circ} = \frac{KT}{q} In \frac{N_d N_a}{n_i^{\ 2}}$$

$$W = \sqrt{\frac{2\varepsilon_s V_\circ}{qN_d}}$$

$$L_e = \sqrt{\frac{\varepsilon_s KT}{q^2 N_d}}$$

$$I_L = qAG(L_e + W + L_h)$$

$$V_{oc} = \frac{KT}{q} In\left(\frac{I_L}{I_\circ} + 1\right)$$

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

$$v_{oc} = \frac{V_{oc}}{KT/q}$$

$$FF = \frac{v_{oc} - In(v_{oc} + 0.72)}{v_{oc} + 1}$$

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

Constants :

K = 1.38 x 10^{-23} , T = 300 ,
q = 1.6 x 10^{-19} , N_a = 2 x10^{16} ,
n_i = 1.45 x 10^{10} ,
ε_s = 105.36498 x 10^{-14} , A = 78.5 ,
G = 3.132705941 x 10^{20} ,
L_h = 0.029188604 x 10^{-4} ,
$I_\circ$ = 7.212641789 x 10^{-13}
Variables : N_d = 10^{13} - 10^{21}

table(2)show the results obtained by run the electronic computer programme in visual basic language

N_d (cm^{-3})	$V_\circ(V)$	$W(\mu m)$	$L_e(\mu m)$	$I_L(A)$	$V_{OC}(V)$	$I_{SC}(A)$	$v_{oc}(V)$	FF	$\eta(\%)$
10^{13}	0.53492127	8.39359645	1.30535408	3.82771015	0.75813847	3.82771015	29.30003764	0.85472410	3.15968563
10^{14}	0.59450066	2.79820367	0.41278920	1.27136608	0.72961970	1.271366061	28.19786288	0.85052126	1.00503847
10^{15}	0.65408005	0.92815092	0.13053540	0.42804383	0.70145161	0.42804383	27.10924124	0.84609732	0.3236209
10^{16}	0.71365944	0.30658341	0.04127892	0.14835742	0.67403443	0.148357425	26.04964004	0.84150367	0.10719579
10^{17}	0.77323882	0.10091598	0.01305354	0.05632812	0.64897629	0.056328123	25.08120958	0.83703127	0.03897859
10^{18}	0.83281821	0.03311907	0.00412789	0.02614026	0.62911161	0.026140262	24.31349241	0.83328200	0.01745661
10^{19}	0.89239760	0.01084132	0.00130535	0.01626410	0.61683350	0.016264104	23.83897615	0.83086752	0.01061842
10^{20}	0.95197699	0.00354092	0.00041278	0.01304043	0.61111757	0.013040435	23.61807061	0.82971688	0.00842320
10^{21}	1.01155638	0.00115424	0.00013053	0.01199029	0.60894518	0.011990296	23.53411335	0.82927501	0.00771324

Conclusion :

From the results , we conclude that

1-The presence of defect (impurities) will decrease(I_{sc} , V_{oc} , η) which is due to the increase of recombination process in the solar cell .

2- Low impurities (10^{13}) lead to high ingot yields and high cell efficiencies . Higher impurities (10^{21}) , cell efficiencies > 16 % can be achieved .

3-The recombination rate increase with increasing the impurity concentrations in the semiconductors , and it is able to make the depletion region width larger by reducing the impurity concentrations .

4-Impurities which offer electron states with energies approximately in the middle of the forbidden zone play the most important role . They capture electrons and holes over a series of excited states , with successive dissipation of energy and degrade the solar cell efficiencies via degradation of the Si minority carrier life times or diffusion lengths .

5-Typical impurity concentrations are in the range of $(10^{15} - 10^{19})$ cm^{-3} . This is relatively small compared with the lattice atom density , which is about 10^{23} cm^{-3} . This is light admixture does not significantly change the chemical nature of the semiconductor .

6-For reaching to efficiency more than 20% , the recombination of the carriers must be reduced by using crystals has long life time of carriers (about 1 ms) .

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