Open Journal of Microphysics, 2012, 2, 27-32
http://dx.doi.org/10.4236/ojm.2012.23004

Modelling, Simulation and Optimization of n-p-n-p Silicon Multilayer Solar Cells

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Received February 10, 2012; revised March 1, 2012; accepted May 9, 2012

ABSTRACT

We simulate the conception parameters of a model of a silicon multilayer solar cell. The cell is composed by four layers of opposite conductivities forming three junctions inside the cell. The electric contacts are tailored vertically to collect the minority carrier generated under illumination. We developed the equations giving the output power, the fill factor and the efficiency of the cell, taking into account the series resistances of each layer. We optimized, using MATLAB software, the thicknesses of the layers, the impurity concentration level and the distance between the electric contacts. We showed that the optimized photovoltaic structure, with the silicon properties published at the Ioffe institute website, gives an efficiency of 20.66%. The n-p-n-p silicon cell delivers a short circuit current I_{cc} = 45.3 mA/cm², an open circuit voltage V_{oc} = 0.746 V and an output power of 28.5 mW/cm². The corresponding fill factor is FF = 84.29%.

Keywords: Solar Cell; Multilayer; Conception; Optimization

1. Introduction

Nowadays, multilayer solar cells occupy a major place in the field of photovoltaic conversion of solar energy, and they are extensively studied [1-4]. These new structures have the advantage of a better collection of the minority carriers generated by the light near the many depletion regions tailored in series inside the cell, each created electron-hole pair can meet, before recombining, a space charge region near the place where it is created.

Considerable research effort, both theoretically and experimentally, has been made to enhance efficiency of multilayer silicon solar cell. K. Brecl *et al.* [5] have developed an extended Ebers-Moll model for the examination of the physical parameters of the multilayer cell. They calculate the current-voltage characteristics of floating junction solar cells. They showed that the photocurrent density produced by an n-p-n-p multilayer solar cell with correspondent layers thicknesses of 0.5 μm, 5.5 μm, 0.4 μm and 30 μm respectively, is equal to 28.19 mA/cm^2 using the global AM1.5 solar spectrum.

In a previous work [6], we simulate and optimize the photocurrent densities in a model of an n-p-n-p type thin film multilayer silicon solar cell for space applications. The equations giving the photocurrent density in each layer of the cell have been developed. We showed that, under the optimum conditions, the n-p-n-p silicon multilayer cell delivers a photocurrent density of 46.28 mA/cm^2. This density of photocurrent represents the short-circuit current I_{cc} that will be used to simulate the *I-V* curves. The optimal thicknesses of the layers define, depending of the impurity concentration, the electrical series resistances of the equivalent electric circuit of the multilayer structure.

In another work [7], a new model of multilayer solar cell has been presented; the cell is composed by four layer of opposite conductivity including a frontal layer of n-type 6H-SiC to absorb high energy photons and a back layer of p-type $Si_{0.8}Ge_{0.2}$ to absorb low energy photons of the solar spectrum. The tow other layers are p-type silicon layer and n-type silicon layer. The optical properties of the semiconductor materials used in this numerical simulation have been taken from the Ioffe institute website [8]. We showed that, under the optimum conditions, such optimized multilayer solar cell could deliver a photocurrent density of 53.5 mA/cm².

2. Optimization of the n-p-n-p Silicon Multilayer Solar Cell

After the optimization of the photocurrent densities produced by the multilayer solar cell by optimizing the layers thicknesses [6], we are interesting in the optimization of the output power and the efficiency of the cell.

An energy band diagram of the multilayer n-p-n-p solar cell is giving below (**Figure 1**). The total thickness of

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the cell is taken equal 100 µm for mechanical rigidity.

The optimal abscissas were [6]: $d_1 = 0.1$ µm, $d_{11} = 0.2$ µm, $d_2 = 13$ µm, $d_{22} = 13.1$ µm, $d_3 = 82$ µm and $d_{33} = 82.1$ µm.

The optimal photocurrent densities, as shown in **Figure 1**, are:

$Jpd_1 = 5.3$ mA/cm^2, $Jnd_{11} = 23.8$ mA/cm^2, $Jnd_2 = 6.9$ mA/cm^2, $Jpd_{22} = 5.4$ mA/cm^2, $Jpd_3 = 2.2$ mA/cm^2, and $Jnd_{33} = 0.23$ mA/cm^2, and the photocurrent densities dues to the space charge regions are:

$Jscr_1 = 2.4$ mA/cm^2, $Jscr_2 = 0.045$ mA/cm^2 and $Jscr_3 = 0.003$ mA/cm^2.

The total photocurrent density produced by the optimized n-p-n-p multilayer silicon solar cell is then *JTot* equal to 46.42 mA/cm^2.

These densities of photocurrent determine the current produced by each junction I_1, I_2 and I_3 in the equivalent electric circuit giving in **Figure 2**. The abscissas of the layers, with the impurity concentration, give the series electrical resistances $R1$, $R2$, $R3$ and $R4$.

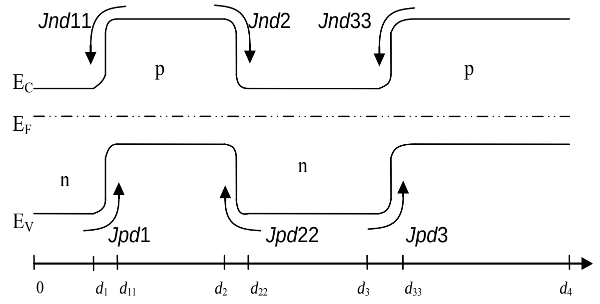


Figure 1. Energy band structure diagram of the multilayer silicon solar cell. The six arrows show the minority carriers path that produces the photocurrent.

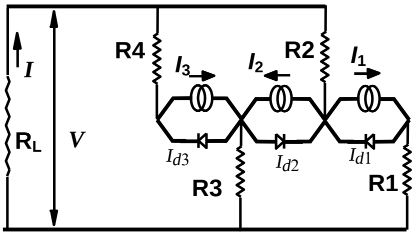


Figure 2. The equivalent electric circuit of the multilayer structure. The arrows show the photocurrent created at each junction.

R_L is the charge resistance and Id_1, Id_2 and Id_3 are the diodes current.

The voltage V can be calculated using three ways:

$$V_1 = \frac{KT}{q}\log\left(1+\frac{Id_1}{I_0}\right) - R_1\left(I_1 - Id_1\right) - R_2\left(I_1 + I_2\right)$$

$$V_2 = \frac{KT}{q}\log\left(1+\frac{Id_2}{I_0}\right) - R_2\left(I_1 + I_2\right) - R_3\left(I_2 + I_3 - Id_2 - Id_3\right)$$

$$V_3 = \frac{KT}{q}\log\left(1+\frac{Id_3}{I_0}\right) - R_4 I_3 - R_3\left(I_2 + I_3 - Id_2 - Id_3\right)$$

where I_0 is the saturation current of the diodes, and is giving by:

$$I_0 = q\left(\frac{p_n D_p}{L_p} + \frac{n_p D_n}{L_n}\right)$$

D_p and D_n are respectively the diffusion coefficient of the holes and the electrons; L_p and L_n are respectively the diffusion length of the holes and electrons; p_n and n_p are the minority carrier concentration (holes and electrons respectively).

The output voltage of the cell is:

$$V = \frac{\left(V_1 + V_2 + V_3\right)}{3}$$

The output current is giving by:

$$I = \left(I_1 + I_2 + I_3\right) - \left(Id_1 + Id_2 + Id_3\right)$$

where:

$$I_1 = Jpd1 + Jscr1 + Jnd11$$

$$I_2 = Jnd2 + Jscr2 + Jpd22$$

$$I_3 = Jpd3 + Jscr3 + Jnd33$$

I_{d1}, I_{d2} and I_{d3} are the diodes currents, they depends of the charge resistance R_L.

The series resistances of each layer are giving by [9]:

$$R_1 = \rho_n \frac{L^2}{2d_1}$$

$$R_2 = \rho_p \frac{L^2}{2\left(d_2 - d_1\right)}$$

$$R_3 = \rho_n \frac{L^2}{2\left(d_3 - d_2\right)}$$

$$R_4 = \rho_p \frac{L^2}{2\left(d_4 - d_3\right)}$$

where, ρ_n and ρ_p are respectively the resistivity of the n-type layer and the p-type layer. L is the distance between the n-contact and the p-contact (see **Figure 3**).

We introduced all the developed equations into MATLAB software to simulate under AM0 solar spectrum the *I-V* characteristics of the cell. The maximum output power $P_{\max}$ can be deduced and the efficiency will be giving by:

$$\eta = \frac{P_{\max}}{0.136}$$

The efficiency depends of the impurity concentration level giving the electrons and holes electrons properties

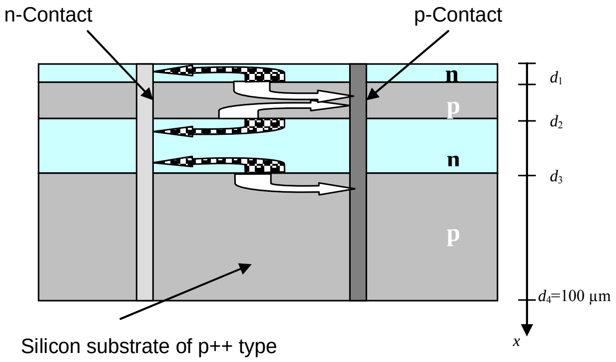


Figure 3. Cross section of the studied n-p-n-p multilayer silicon solar cell, the light enters from the n-side.

(L_n, D_n and L_p, D_p). It depends also, of the layers thickness (d_1, $d_2 - d_1$, $d_3 - d_2$ and $d_4 - d_3$) in terms of the series resistances, and of the distance L between n-contacts and p-contact. The optimization of the photovoltaic structure supposes three steps:

1) Optimization of the layers thickness;
2) Optimization of the impurity concentration;
3) Optimization of the distance between contacts.

2.1. Optimization of Layers Thicknesses

We begin by optimizing the layers thicknesses defined by the abscissas d_1, d_2, d_3 and d_4. We computed the efficiency of the n-p-n-p silicon solar cell by varying all the abscissas in a three dimensional space d_1, d_2 and d_3. The abscissa d_4 is fixed equal to 100 µm which represents the total cell thickness. The impurity concentration is taken equals 10^{17} cm^{-3} in all the photovoltaic structure to ensure. As an illustration, **Figure 4** gives the efficiency of the n-p-n-p solar cell versus the first and the second layer abscissa.

We can see that the efficiency of the cell decreases when d_1 and d_2 increases.

The program of simulation written in MATLAB gives the three optimal abscissas and the maximum efficiency under the prefixed simulation conditions:

$d_{1\text{opt}} = 4$ µm, $d_{2\text{opt}} = 10$ µm, $d_{3\text{opt}} = 45$ µm and $\eta_{\max} =$ 19.78%. Many other combinations of layers thickness giving the same value of the efficiency are possible.

2.2. Optimization of the Impurity Concentration

Here we optimize the impurity concentration using the optimal values of layers thicknesses. We simulate, under AM0 solar spectrum and assuming 100 cm/s surface recombination velocity, the *I-V* characteristics of the n-p-n-p solar cell for different values of the impurity concentration going from 10^5 cm^{-3} to 10^{19} cm^{-3}.

The electrical properties and the recombination parameters, depending of the impurity concentration were taken from Ioffe institute website [7] and given in **Table 1**.

We reported in **Table 2** the results of simulation corresponding to the different values of the impurity concentration.

The efficiency of the simulated cells varies from 2.53% for an impurity concentration of 10^{15} cm^{-3} to 21.09% for an impurity concentration of 10^{18} cm^{-3}. **Figure 5** gives the *I-V* characteristic corresponding to an impurity concentration of 10^5 cm^{-3} (**Figure 5(a)**) and 10^{18} cm^{-3} (**Figure 5(b)**).

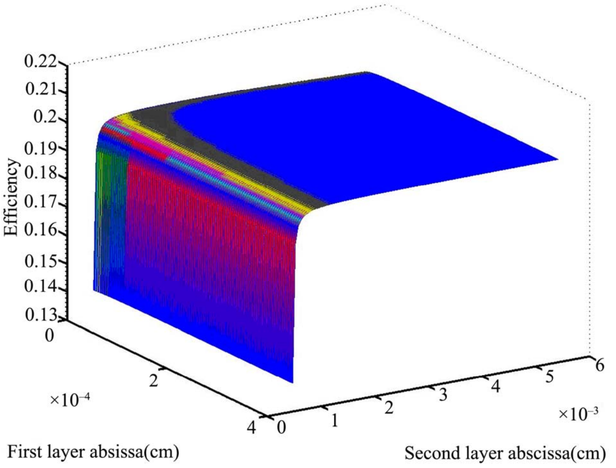


Figure 4. Efficiency of the n-p-n-p solar cell versus the first and the second layer abscissa. The third layer abscissa *d*3 is taken equal to 60 µm.

Table 1. Recombination parameters versus impurity concentration.

	Impurity concentration (cm^{-3})	10^{15}	10^{16}	10^{17}	10^{18}	10^{19}
n type	Lifetime τ_n (s)	1.8×10^{-4}	7.4×10^{-5}	2.5×10^{-5}	4×10^{-6}	1.1×10^{-7}
	Diffusion length L_n (cm)	0.08	0.05	2.2×10^{-2}	4.3×10^{-3}	4.5×10^{-5}
	Diffusion coefficient D_n (cm²/s)	45.71	33.79	19.36	4.62	1.84
	Resistively ρ_n (Ω-cm)	5	0.58	0.09	2.2×10^{-2}	5×10^{-3}
p type	Lifetime τ_p (s)	1.9×10^{-4}	7×10^{-5}	1.5×10^{-5}	1.4×10^{-6}	5.3×10^{-8}
	Diffusion length L_p (cm)	0.041	0.024	0.008	1.7×10^{-3}	2.2×10^{-4}
	Diffusion coefficient D_p (cm²/s)	8.84	8.23	4.26	2.06	0.91
	Resistively ρ(Ω-cm)	14	1.8	0.22	4.5×10^{-2}	9×10^{-3}

The efficiency of the n-p-n-p silicon multilayer solar cell corresponding to an impurity concentration of 10^5 cm^{-3} is too week (less then 3%). This is due to the lack of minority carriers to be generated under illumination.

The efficiency of the cell decreases with an impurity concentration of 10^{19} cm^{-3} and it doesn't exceed 17%. This low efficiency is due to the high recombination possibility and the important values of layers resistances, which depends on the minority carriers electrical properties as giving above.

We can see from **Table 2** that the maximum efficiency is obtained with an impurity concentration of 10^{18} cm^{-3}. Thus, the optimal concentration is in proximity of 10^{18} cm^{-3}. We computed our simulation using an impurity concentration level between 3×10^{17} cm^{-3} and 5×10^{18} cm^{-3}. The optimal impurity concentration is obtained equals to 10^{18} cm^{-3}.

2.3. Optimization of the Distance between Electric Contacts

In all our previous simulation we considered that the electric contact thickness is negligible and that there are no losses of light absorption at the front surface of the cell. In reality, this is not totally true. In fact, the surface of the electric contacts tailored inside the cell causes a significant loss of light absorption under illumination. Consider that the contact thickness is S_{contact} equal to 5 µm, which is a realistic value, and that the number of contacts per square centimetre is k equal to 15. The remaining illuminated surface of the cell will be:

$$S_{\text{remaining}}(\text{cm}^2) = 1 - k \cdot S_{\text{contact}} = 0.9925$$

Table 2. Results of impurity concentration optimization.

Impurity concentration (cm^{-3})	10^{15}	10^{16}	10^{17}	10^{18}	10^{19}
Short-circuit current (mA/cm²)	47.4	46.6	46.3	46.0	37.0
Open circuit voltage (V)	0.35	0.62	0.68	0.75	0.74
Output power (mW/cm²)	3.40	23.7	26.9	28.7	22.6
Fill factor (%)	20.83	82.86	84.27	83.36	82.56
Efficiency (%)	2.53	17.44	19.75	21.09	16.61

The flux of light received by the photovoltaic cell is:

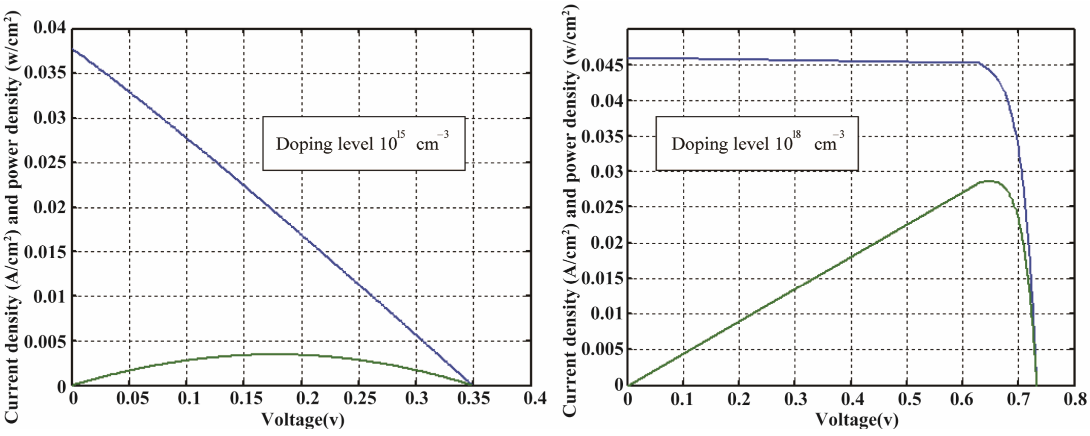
$$\varphi_{\text{received}} = \varphi_{\text{total}}\left(1 - k \cdot S_{\text{contact}}\right)$$

We computed our MATLAB program taking in account the received quantum of incident photon energy, and we simulate the efficiency of the n-p-n-p silicon multilayer solar cell for different values of the contact thickness. The program of simulation gives the optimal number of contacts and the optimal distance between contacts giving the maximum efficiency for each value contact thickness.

We use the optimal layers thicknesses obtained in 2.1 and the optimal impurity concentration obtained in 2.2. **Figure 6** gives the simulated efficiency versus the contact thickness and the distance between contacts.

We can see from the three dimensional curve, that for each contact thickness correspond an optimal distance between contacts which gives the maximum efficiency of the cell. **Table 3** resumes the optimal distance between contacts (d_{contacts}) and the maximum efficiency obtained with some choosing values of the contact thickness S_{contact}.

The efficiency of the conceived multilayer solar cell decreases when the thickness of the electric contacts increases. This efficiency drop is due to the non-illuminated surface resulting from the some of electric contact thicknesses. The efficiency of the n-p-n-p silicon solar cell, with a contact thickness of 0.1 µm is equal to 20.6%. The efficiency of the cell decreases to only about 15% with a contact thickness of 5 µm. Thus, special care may be accorded to the insertion or the growth of the electric contacts to achieve high efficiency values.



(a) (b)

Figure 5. *I-V* characteristics of the n-p-n-p silicon solar cell with an impurity concentration of 10^{15} cm^{-3} (a) and 10^{18} cm^{-3} (b).

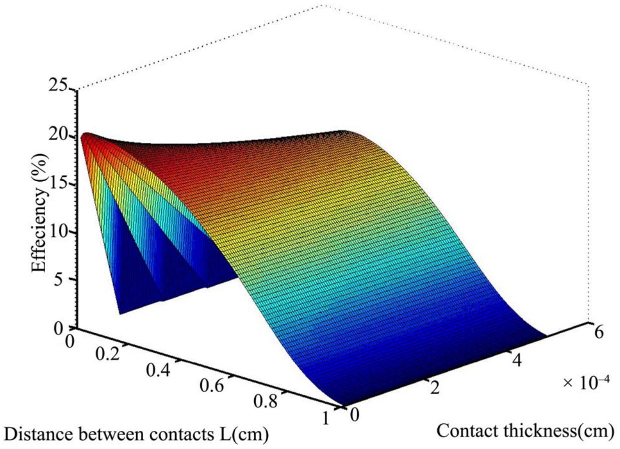


Figure 6. Efficiency versus contact thickness and distance between contacts.

Table 3. Optimal efficiency and distance between contacts for different values of contacts surface.

$S_{contact}$ (µm)	0.1	1	1.5	2	3	5
$d_{contacts}$ (cm)	0.07	0.15	0.17	0.19	0.21	0.26
Optimal Efficiency (%)	20.6	19.0	18.4	17.8	16.9	15.3

3. Conclusions

In this work we optimized the conception parameters of a proposed n-p-n-p multilayer solar cell composed by four layers of opposite conductivities forming three junctions inside the cell. The electric contacts are tailored vertically to collect the minority carrier generated under illumination.

The optimization of the cell conception was accomplished within three steps: optimization of the layers thicknesses, optimization of the impurity concentration and optimization of the distance between electric contacts. The optimization of the layers thicknesses takes into account the series resistances of each layer which determine the voltage drop inside the cell.

The optimization of the impurity concentration is based on the research of the best compromise between lacks and exceeds of electric carrier to be generated under illumination. Finally the distance between electric contacts was optimized tacking into account the non-illuminated surface due to the contact thicknesses.

The optimal parameters are:

Optimal layers abscissas:

d_1 = 4 µm for the first layer;

d_2 = 10 µm for the second layer;

d_3 = 45 µm for the third one;

The optimal impurity concentration: 10^{18} cm^{-3};

The optimal electric contact thickness: 0.1 µm;

The optimal distance between contacts: 0.07 cm.

The optimized photovoltaic structure, with the silicon properties published at the Ioffe institute website [Ioffe], gives an efficiency of 20.66%. The n-p-n-p silicon cell deliver a short circuit current I_{cc} = 45.3 mA/cm², an open circuit voltage V_{oc} = 0.746 V and an output power of 28.5 mW/cm². The corresponding fill factor is *FF* = 84.29%.

These values of the cell performances can be improved by using a best quality of silicon like those used by M. Green in PERC and PERL cells [10] and by using a square based pyramids surface in the front face of the cell.

4. Acknowledgements

We are grateful an anonymous referee for helpful comments. We also wish to thank Kim Humphreys for English editing. All errors are ours.

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