Maximizing the photocurrent density in a p-n-p-n silicon multilayer solar cell

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Résumé : Les cellules solaires multijonction occupent une place majeure dans le domaine de la conversion photovoltaïque de l’énergie solaire. Ces nouvelles structures présentent l’avantage d’une meilleure collecte des porteurs de charges générés par effet photovoltaïque en minimisant les pertes dues à leurs recombinaisons. En effet, en introduisant plusieurs jonctions dans la structure multicouches, tout porteur de charge (électron ou trou) généré rejoint rapidement la jonction la plus proche de lui et contribue ainsi à l’augmentation du photocourant total généré par la cellule.

On se propose dans ce travail, de modéliser et de simuler une structure de cellule solaire photovoltaïque multijonction à base de silicium formée par quatre couches de type p-n-p-n. Nous avons élaboré les équations donnant le photocourant produit par chaque couche ; l’optimisation des différents paramètres a été réalisée en utilisant le logiciel Matlab. Nous avons montré que la cellule optimisée peut délivrer un courant total supérieur à 36 mA/cm², dépassant de loin celui délivré par une cellule classique à simple jonction p-n.

Mots clés : Photovoltaïque, multicouches, modélisation, simulation.

Abstract: In this work, we study a model of a multilayer silicon solar cell composed by four layers p-n-p-n, including three p-n junctions. The model is simulated using realistic parameters values. The solar spectrum air mass 0 (AM0) was used to calculate the photocurrent density. The equations giving the photocurrent density produced in each abscissa of the structure was developed. We used Matlab software to simulate and optimize the different parameters of the model. The results of simulation showed that after optimization, such structures could deliver a photocurrent density of more than 36 mA/cm², which is very high compared to the classical p-n simple junction solar cell. The simulation took into account the effect of the surface recombination velocity, which is the most important perturbation against the collection of the charge carrier.

Key words: Photovoltaic, multilayer, modeling, simulation.
Introduction

Nowadays, multilayer solar cells occupy a major place in the field of photovoltaic conversion of solar energy, and they are extensively studied both theoretically and experimentally [1 - 5]. 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.

Our model of silicon multilayer solar cell is composed by four successive layers of opposite conductivity p-n-p-n type as shown in figure 1. Any electron-hole pair created in each layer of the cell meets the nearest depletion region and is separated, so the hole joins the n-contact and electron joins the p-contact. The total photocurrent density produced by the cell under Air Mass 0 solar spectrum illumination is the sum of the photocurrents density produced in each layer of the cell and the photocurrent density produced inside the three depletion regions. Our objective is to find the optimum layers thicknesses that give the maximum photocurrent density.

![Fig.1: Schematic diagram of the model of four layers of opposite conductivities p-n-p-n silicon multilayer solar cell.](image)

Photocurrent density calculation

The photocurrent density results from the minority carrier collection. The electron-hole pairs created inside the cell by the absorption of the sun light are collected when they reach a space charge region. This collection may be disturbed by bulk recombination and surface recombination. Multilayer solar cell presents the advantage of a better collection of the charge carrier by introducing many depletion regions inside the cell, which make the path of the carrier lower than the diffusion length $L = \sqrt{D\tau}$, where D is the minority carrier diffusion coefficient and $\tau$ the minority carrier lifetime [3].

In our model, there are seven regions where the absorbed light creates electron-hole pairs: two p regions, two n regions and three space charge regions. In our simulation, we will calculate the photocurrent density produced in each region and add them to obtain the photocurrent density produced by the cell.

Figure 2 shows the band structure diagram of the multilayer silicon solar cell of our model. The region between the abscissa $d_1$ and $d_{11}$ represents the first space charge region, the region between $d_2$ and $d_{22}$ represents the second space charge region and the region between $d_3$ and $d_{33}$ represents the third space charge region. $J_{pd1}$ represents the photocurrent density that outcomes from the light absorbed in the first layer, $J_{pd11}$ and $J_{pd2}$
represents the photocurrent density that results from the absorbed light in the second layer, $J_{nd2}$ and $J_{nd3}$ represents photocurrent density that results from the absorbed light in the third layer. Finally, $J_{pd33}$ represents the photocurrent density that results from the absorbed light in the four layer of n-type.

![Band structure diagram of the multilayer silicon solar.](image)

Fig. 2: Band structure diagram of the multilayer silicon solar.

In the space charge region, we assume that there is no recombination and that every photon absorbed gives rise to an electron-hole pair. The photocurrent density due to the space charge region 1, delimited by $d_1$ and $d_{11}$ on its border is:

$$J_{scr1} = q\phi[\exp(-\alpha d_1) - \exp(\alpha d_{11})]$$  \hspace{1cm} (1)

Where $\alpha$ is the absorption coefficient of the silicon and $\phi$ is the photon flux. The other photocurrent density are similar and are given by:

$$J_{scr2} = q\phi[\exp(-\alpha d_2) - \exp(\alpha d_{22})]$$  \hspace{1cm} (2)

$$J_{scr3} = q\phi[\exp(-\alpha d_3) - \exp(\alpha d_{33})]$$  \hspace{1cm} (3)

In n or p-type regions, the classical diffusion equations are:

In the n region:

$$D_n \frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_n} + G(x) = 0$$  \hspace{1cm} (4)

and in the p region:

$$D_p \frac{\partial^2 p}{\partial x^2} - \frac{p}{\tau_p} + G(x) = 0$$  \hspace{1cm} (5)

Where $p$ and $n$ are the concentration of the minority carriers, $D$ is the diffusion coefficient, $\tau$ is the lifetime and $G(x)$ is the generation function given by:

$$G(x) = \phi(\lambda)\alpha(\lambda)\exp(-\alpha(\lambda)x)$$  \hspace{1cm} (6)

The boundary conditions to solve these equations are as follows [4]:

$$qD_n \frac{\partial n}{\partial x} \bigg|_{x=0} = qnS \text{ and } n(d_1) = 0.$$  \hspace{1cm} (7)

$$p(x) = 0 \text{ at } x = d_{11} \text{ and } x = d_2$$  \hspace{1cm} (8)

$$n(x) = 0 \text{ at } x = d_{22} \text{ and } x = d_3$$  \hspace{1cm} (9)

$$p(x) = 0 \text{ at } x = d_{33}$$  \hspace{1cm} (10)
\[ qD_p \frac{\partial p}{\partial x} \bigg|_{x=d} = qpS' \]  

The photocurrent density is calculated from the concentration of the minority carrier as follows:

\[ J_p = qD_p \frac{\partial p}{\partial x} \]  

for the holes in the n-type region, and

\[ J_n = -qD_n \frac{\partial n}{\partial x} \]  

for the electrons in the p-type regions

We give below the equations that express the minority carrier concentration versus the abscissa \( x \) in each layer of the cell. The photocurrent density is calculated using equations (12) and (13).

For the first layer; \( x \) between 0 and \( d_1 \), the concentration of the excess minority carrier (electrons) is given by:

\[
n(x) = \frac{\alpha \phi L_n}{D_n(1-\alpha^2 L_n^2)} \left[ L_n \left( \frac{S}{D_n} + \alpha \right) \sinh \left( \frac{x-d_1}{L_n} \right) - e^{-\alpha d_1} \left( \cosh \left( \frac{x}{L_n} \right) + \left( \frac{S}{D_n} \right) \sinh \left( \frac{x}{L_n} \right) \right) + e^{-\alpha x} \right] \]

The photocurrent density produced at \( x = d_1 \) is given by:

\[
J_{n,d_1} = \frac{q \alpha \phi L_n}{1-\alpha^2 L_n^2} \left\{ \alpha L_n e^{-\alpha d_1} - \frac{S L_n}{D_n} + \alpha L_n - e^{-\alpha d_1} \left( \sinh \left( \frac{d_1}{L_n} \right) + \frac{S L_n}{D_n} \cosh \left( \frac{d_1}{L_n} \right) \right) \right\} \]

For the second layer; \( x \) between \( d_1 \) and \( d_2 \), the concentration of the holes is:

\[
p(x) = \frac{\alpha \phi L_p}{D_p(1-\alpha^2 L_p^2)} \left\{ e^{-\alpha d_1} \sinh \left( \frac{x-d_2}{L_p} \right) - e^{-\alpha d_2} \sinh \left( \frac{x-d_1}{L_p} \right) \right\} \]

\[
J_{p,d_1} = -\frac{q \alpha \phi L_p}{1-\alpha^2 L_p^2} \left\{ \alpha L_p e^{-\alpha d_1} - \frac{e^{-\alpha d_1} \cosh \left( \frac{d_1-d_2}{L_p} \right) - e^{-\alpha d_2}}{\sinh \left( \frac{d_2-d_1}{L_p} \right)} \right\} \]

\[
J_{p,d_2} = \frac{q \alpha \phi L_p}{1-\alpha^2 L_p^2} \left\{ \alpha L_p e^{-\alpha d_2} - \frac{e^{-\alpha d_1} - e^{-\alpha d_2} \cosh \left( \frac{d_2-d_1}{L_p} \right)}{\sinh \left( \frac{d_2-d_1}{L_p} \right)} \right\} \]

For the third layer; \( x \) between \( d_2 \) and \( d_3 \):
Optimizing the photocurrent density

The realistic parameters used to simulate our model are \( D_p = 1.35 \text{ cm}^2/\text{s} \) and \( \tau_p = 0.4 \mu\text{s} \) for the n-type regions, and \( D_n = 300 \text{ cm}^2/\text{s} \) and \( \tau_n = 0.01 \mu\text{s} \), which characterize a low quality material. The surface recombination velocity is equal to \( S = 10^5 \text{ cm/s} \). The simulation is done under the solar spectrum Air Mass 0 (AM0) [3]. We maximized the photocurrent density layer by layer by varying the abscissas in equations (15, 17, 18, 20, 21 and 23) using Matlab software. The results of simulation are presented in the figures 3, 4 and 5; we can verify that all the boundary conditions that we defined to solve the differential equations are respected.

We begin by checking the first layer thickness \( d_1 \) that gives the maximum photocurrent density produced by the layer using equation (15); this gives the optimal first layer thickness \( d_1 \) equals to 6 \mu m. This photocurrent density \( J_{nd1} \) equals 27.5 mA/cm\(^2\) (figure 3).

The second layer photocurrent density is simulated using the optimal thickness \( d_1 \), and by varying \( d_2 \) in the equations (17) and (18). The maximum photocurrent density is obtained for an optimal second layer abscissa \( d_2 \) equals to 22.5 \mu m, and it gives \( J_{pd11} \) equals to 4.2 mA/cm\(^2\) and \( J_{pd22} \) equals to 1.8 mA/cm\(^2\) (figure 4).
The photocurrent densities produced by the third layer are $J_{nd22}$ and $J_{nd3}$. In the figure 5, we simulate the sum of the two current densities versus the third layer thickness $d3$. The results of simulation showed that the maximum is obtained for an abscissa $d3$ equal to 64 $\mu$m and it gives $J_{nd22}$ equal to 1.9 mA/cm² and $J_{nd3}$ equal to 1.1 mA/cm².

For the last layer, the produced photocurrent density is $J_{pd33}$ and it is function of the abscissa $d3$ as shown in the equation (23). The optimal abscissa $d3$ which is equal to 64 $\mu$m gives $J_{pd33}$ equal to 0.3 mA/cm².
Results and discussion

The maximum photocurrent density produced by the first layer, using the above fixed parameters of our model is obtained for a layer thickness $d_1$ equals to 6 µm as shown in figure 3. The optimal photocurrent density is equal to $J_{nd1_{max}} = 27.5$ mA. Figure 4 represents the resulting simulation of the second layer photocurrent density. The optimal abscissa $d_2$ is equal to 22.5 µm and it gives $J_{pd11}$ equal to 4.2 mA/cm² and $J_{pd2}$ equal to 1.8 mA/cm². The total photocurrent density produced by the second layer is then equal to 6 mA/cm².

The optimal abscissa $d_3$ is equal to 64 µm and it gives $J_{nd22}$ equal to 1.9 mA/cm² and $J_{nd3}$ equal to 1.1 mA/cm². The total photocurrent produced by the third layer is equal to 3 mA/cm². The last layer photocurrent is given by $J_{pd33}$ and it is equal to 0.1 mA/cm². We note that $J_{pd33}$ is insignificant compared to the photocurrent densities produced by the other layers of the cell, so that it will not considered in our future work.

The photocurrent densities produced by the three space charge regions are as follows:

The first space charge region delimited by $d_1 = 6$ µm and $d_{11} = 6.1$ µm: $J_{scr1} = 0.12$ mA.

The second space charge region delimited by $d_2 = 22.5$ µm and $d_{22} = 22.6$ µm: $J_{scr2} = 0.02$ mA.

The third space charge region delimited by $d_3 = 64$ µm and $d_{33} = 65$ µm: $J_{scr3} = 0.04$ mA.

The total photocurrent densities produced by the three space charge regions is $J_{scr}$ equals to 0.16 mA/cm² which is negligible compared to the total photocurrent density produced by the multilayer solar cell; the most important components of the total photocurrent is due to the collection which happens on both side of the space charge regions, namely $J_{nd1}$, $J_{pd11}$, $J_{pd2}$, $J_{nd22}$ and $J_{nd3}$.

Finally, the total photocurrent densities produced by the optimised multilayer solar cell under AM0 solar spectrum and for a surface recombination velocity of $10^5$ cm/s is $J_{total}$, which equals 36.4 mA/cm², which is very high compared to the classical simple junction solar cell.

Effect of the surface recombination velocity

The effect of surface recombination velocity, which is the most important perturbation against the collection of the charge carrier, was simulated. We present in the figure 6 the resulting curve giving the photocurrent density in the first layer $J_{nd1}$ versus the first layer thickness $d_1$ for different values of the surface recombination velocity: $S = 10^3$ cm/s, $S = 10^4$ cm/s, $S = 10^5$ cm/s and $S = 10^6$ cm/s. We can see that the optimal thickness of the layer which gives the highest photocurrent density is decreasing while increasing the surface recombination velocity value. For the larger values of the surface recombination velocity ($S = 10^6$ cm/s and $S = 10^5$ cm/s), the optimal layer thickness is between 2 µm and 3 µm. for much smaller surface recombination velocity, the optimal thickness of the layer is greater than 4 µm, and the maximum of the photocurrent density reaches more than 30 mA/cm².
Summary and Conclusion

The recently developed multilayer cell concept has the advantage of a better carrier collection in low quality materials. In this work, a model of a silicon multilayer solar cell was simulated using realistic parameters with a middle quality material. The cell is composed of four layers of p-n-p-n type, including three space charge regions. The photocurrent density produced by each layer of the cell was maximized versus the variation of the thickness. The optimal thickness of the layers gives rise to a total photocurrent density of more than 36 mA/cm².

References