

Improving the performance of pin solar cell by optimizing its active layer

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Abstract. Efficiency of solar cell depends on absorbed photons and electron-hole pairs (carriers) generated in space charge region, the thickness of which has to be well chosen since the photocurrent is essentially due to the photogeneration of carriers in this region. It is therefore wise to artificially increase thickness of the space charge region by interposing an intrinsic layer I between the regions P and N, to obtain a PIN solar cell. In hydrogenated amorphous silicon (a-Si:H) PIN solar cell, a thick absorber layer (i-layer) can absorb more light to generate carriers, however, a thicker i-layer degrades drift electric field for carrier transport. On the other hand, a thin i-layer cannot absorb enough light. Thickness of i-layer is a key parameter that can limit the performance of amorphous thin film solar cells. In this context, we sought to improve the performance of PIN solar cell by optimizing the i-layer thickness. For this purpose, we have used Matlab software to carry out our simulations. Maximum efficiency of the cell is obtained at the 1.1 μm of thickness of i-layer.

Keywords. Solarcell, PIN structure, conversion efficiency, optimization, simulation.

AMS Classification:

I. Introduction

Generally, the single junction a-Si:H cell uses p-type layers of a-SiC:H semiconductor deposited on n-type a-Si:H semiconductor, with an intermediate intrinsic layer between p- and n-type layers. In this research, intrinsic a-Si:H layer is used, the choice of this material is justified by its low defect density, which gives to charge carriers in the depletion region a relatively long lifetime [1]. Also a-Si:H is a good absorber of light (absorption coefficient $>10^5\text{cm}^{-1}$). However, the light-induced degradation of a-Si:H reduces the lifetime of carriers and the electric field in intrinsic layer degrades efficiency of the a-Si:H solar cell [2].

In order to improve the stability of solar cells, one way is to reduce the thickness of intrinsic layer to increase the electric field in that layer, which makes the solar cell less sensitive to light. However,

when intrinsic layer is too thin, solar cell efficiency is limited by the amount of absorbed light. A good compromise is needed to improve performance of the PIN solar cell.

In order to find the optimal thickness and effectiveness by numerical simulation, we vary the thickness of i-layer in ranges from 0.1 to 5 μm .

1. PHYSICS OF PIN STRUCTURE SOLAR CELL

The PIN silicon solar cell structure is shown in figure 1. It has an intrinsic layer which differs it from standard p-n solar cell. The existing layer is undoped and located between p-layer which is the emitter and n-layer which is the base. Addition of i-layer is needed because amorphous silicon solar cell has narrower depletion region area than crystalline. The three layers present in the PIN solar cell are very thin extrinsic layers and thicker intrinsic layer

[3]. The optical generation is also represented by phototransport mechanism.

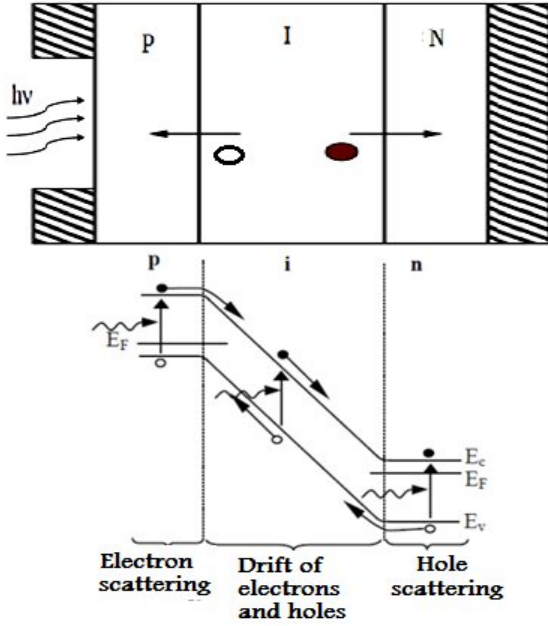


Fig.1. Schematic view and phototransport mechanism of PIN solar cell.

II. Modeling the photocurrent of charge carrier generation

The J_{ph} photocurrent of solar cell defines the amount of electron-hole pairs created crossing the junction without recombination, it results from the sum of three components:

- The diffusion current of photoelectrons in p-layer.
- The photogeneration current in intrinsic layer.
- The diffusion current of photoholes of the n-layer.

The photocurrent calculation is obtained by summing all of these components at $x = x_n$ (Fig. 2).

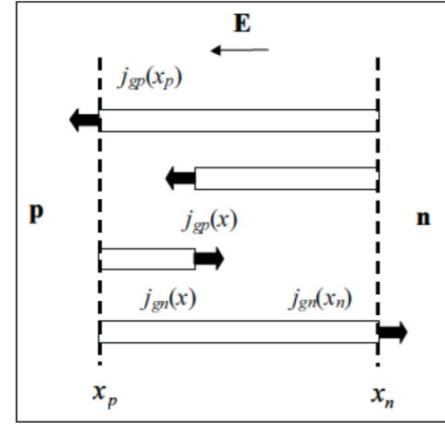


Fig.2. Currents in a PIN cell

Illumination of the solar cell with a photon flux Φ of energy greater than the band-gap width causes absorption of photons and generation of additional electron-hole pairs. As a result of the generation, an increase in the concentration of the excess electrons and holes in the three layers present in the PIN solar cell takes place. Since the absorption coefficient is α , the rate of the electron-hole pairs generation as a function of the depth from the surface of the illuminated p-layer can be expressed by the following formula[4]:

$$g(x) = \Phi \alpha e^{-\alpha x} \quad (1)$$

A. Scattering current of electrons in p-layer

In p-layer, the electrons created (minority) diffuse towards the i-layer. By neglecting the electric field in this area, minority carrier diffusion is written as[5]:

$$\frac{d^2 \Delta n}{dx^2} - \frac{\Delta n}{L_n^2} = -\frac{\Phi \alpha \tau_n}{L_n^2} e^{-\alpha x} \quad (2)$$

With Δn the excess electrons in the p-layer, L_n the diffusion length of electrons and τ_n their lifetime.

Assuming that all electrons having reached the i-layer are propelled to the right by the electric field E , and the surface recombination at $x = 0$ is s_0 , we obtain as boundary conditions for expression “(2)”:

$$\left(\Delta n(x = x_p) = 0 \text{ and } D_n \frac{d\Delta n}{dx} \Big|_{x=0} = -s_0 \Delta n(0) \right) \quad (3)$$

We obtain the expression for Δn , by using the integration constants A_n and B_n calculated with the boundary conditions “(3)”:

$$\left(\begin{array}{l} \Delta n \left(\frac{x}{L_n} \right) e^{-\frac{x}{L_n}} + B_n e^{\frac{x}{L_n}} + \frac{\Phi \alpha \tau_n}{1 - \alpha^2 L_n^2} e^{-\alpha x} \end{array} \right) \quad (4)$$

The current of electron scattering at $x = x_p$ is expressed by:

$$\left(\begin{array}{l} J_{ndiff}(x_p) = q D_n \frac{d \Delta n}{dx} \Big|_{x_p} \end{array} \right) \quad (5)$$

$$J_{ndiff}(x_p) = q D_n \left[\frac{A_n}{L_n} e^{-\frac{x_p}{L_n}} + \frac{B_n}{L_n} e^{\frac{x_p}{L_n}} - \frac{\Phi \alpha \tau_n}{1 - \alpha^2 L_n^2} e^{-\alpha x_p} \right] \quad (6)$$

By neglecting the recombination in i-layer, all the electrons arriving at $x = x_p$ are found at $x = x_n$, thus leading to:

$$J_{ndiff}(x_n) = J_{ndiff}(x_p). \quad (7)$$

B. Scattering current of holes in n-layer

In n-layer, the holes created (minority) diffuse towards the intrinsic layer. By neglecting the electric field in this area, the continuity equation of the excess holes Δp is written[5]:

$$-\frac{d^2 \Delta p}{dx^2} - \frac{\Delta p}{L_p^2} = \frac{\alpha \tau_p}{L_p^2} e^{-\alpha x} \quad (8)$$

with L_p the holes diffusion length and τ_p their lifetime.

Holes reaching the i-layer are evacuated to the left, and it is considered that L (length of the structure) is sufficiently large compared to L_n and $1/\alpha$. The boundary conditions are therefore:

$$\left(\begin{array}{l} \Delta p(x=L) \rightarrow \infty = 0 \text{ et } \Delta p(x=L) = 0 \end{array} \right) \quad (9)$$

By using these boundary conditions, one obtains:

$$\left(\begin{array}{l} \Delta p(x) = \frac{\Phi \tau_p}{1 - \alpha^2 L_p^2} e^{-\alpha x_n} \left(e^{-\alpha(x-x_n)} - e^{-(x-x_n)/L_p} \right) \end{array} \right) \quad (10)$$

The hole diffusion current at $x = x_n$ is expressed by:

$$\left(\begin{array}{l} J_{pdiff}(x_n) = -q D_p \frac{d \Delta p}{dx} \Big|_{x_n} = -q \Phi \frac{\alpha L_p}{1 + \alpha L_p} e^{-\alpha x} \end{array} \right) \quad (11)$$

C. Generation current in i-layer

Neglecting recombination in the intrinsic zone, the steady state continuity equation for the electron generation current is written:

$$-\frac{1}{q} \frac{d J_{gs}}{dx} + g(x) = 0 \quad (12)$$

Integration of“(12)”leads to:

$$J_{gn}(x_n) - J_{gp}(x_p) = -q \int_{x_p}^{x_n} g(x) dx = -q \int_{x_p}^{x_n} \Phi \alpha e^{-\alpha x} dx \quad (13)$$

The electron generation current is created from x_p to x_n , so $J_{gp}(x_p)$ is zero. We obtain after integration:

$$\left(\begin{array}{l} J_{gn}(x_n) = -q \Phi (e^{-\alpha x_p} - e^{-\alpha x_n}) \end{array} \right) \quad (14)$$

We can similarly calculate the hole generation current, created from x_n to x_p . This current is zero at $x = x_n$ and the total generation current at $x = x_n$ is therefore equal to the electron generation current:

$$\left(\begin{array}{l} J_g(x_n) = J_{gn}(x_n) \end{array} \right) \quad (15)$$

D. Total photocurrent

Total photocurrent J_{ph} is the sum of the currents described by expressions“(6)”,“(11)”,“(14)” and“(15)”. The p-layer is in practice thin so that the number of electron-hole pairs created in i-layer is large. In this case, we can neglect electron scattering current“(6)”and consider that $x_p \approx 0$ and $x_n \approx W_i$ (width of the i-layer). We finally get:

$$\left(\begin{array}{l} J_{ph} = J_g(x_n) + J_{pdiff}(x_n) = -q \Phi \left(1 - \frac{1}{1 + \alpha_p L_p} e^{-\alpha W_i} \right) \end{array} \right) \quad (16)$$

II. REAL MODEL OF THE PIN SOLAR CELL

The one-diode model is the most popular to represent a solar cell thanks to its simplicity and precision [6]. In a PIN solar cell, the phenomenon of recombination represents significant losses; which cannot be properly modelled using the one diode model. Consideration of these losses leads to

introduce an additional diode [7,8]. The equivalent electrical circuit of the model is shown in figure 3.

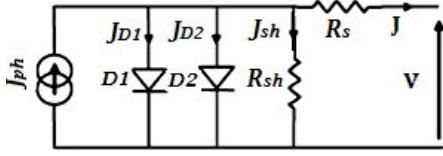


Fig. 3: Equivalent electrical circuit of solar cell, Two diode model

The output current is given by “(17)”[9].

$$J = J_{ph} - J_{s1} \left(\exp \frac{V + R_s J}{n_1 \cdot V_T} - 1 \right) - J_{s2} \left(\exp \frac{V + R_s J}{n_2 \cdot V_T} - 1 \right) - \frac{V + R_s J}{R_{sh}} \quad (17)$$

With: J_{ph} , Photocurrent of the cell; J_{s1} and J_{s2} are the reverse saturation currents of diode D1 and diode D2 respectively. The term containing J_{s2} in “(17)” compensates the loss by recombination in the space charge region as described in [10].

The factors n_1 and n_2 represent components of the diffusion and recombination current respectively. According to Shockley’s diffusion theory, n_1 should equal unity [10]. The value of n_2 can vary. A better compatibility is obtained between the proposed model and the experiment if $n_2 \geq 1,2$.

The series resistance R_s is due to contribution of base and emitter resistances and contacts of front and rear faces. The shunt resistance R_{sh} is due to a leakage current at the junction.

$V_T = kT/q$ is the thermal voltage; k , Boltzmann constant; q , Electron charge; T , Cell temperature.

Reverse saturation currents are given by [11] :

$$J_{s1} = q n_i^2 \left(\frac{D_{pn}}{L_{pn} N_D} + \frac{D_{np}}{L_{np} N_A} \right); (A.cm^{-2}) \quad (17)$$

$$J_{s2} = \frac{q W_i}{2} \cdot \frac{n_i}{\tau} \quad (18)$$

With: W_i , the thickness of i-layer; n_i , the intrinsic density; τ , the lifetime.

III. Results and discussion

Throughout this work, the standard conditions for qualifying solar cells are used: AM1.5 and a temperature of 300 ° K. We start the simulation of a PIN solar cell shown in Fig.1. Then we go to optimize the parameter having a great influence on the efficiency of the cell in order to obtain the optimum performance there is. The parameter in question is the thickness of the active layer .

A. $J(V)$ and $P(V)$ characteristics

Figure 4 and figure 5 express the $J(V)$ and $P(V)$ characteristics of a PIN solar cell. A lot of parameters relating to solar cell circuit could be extracted from these curves such as J_{cc} , V_{oc} . J_{cc} represents the maximum density current at short circuit circumstance and reflects the capability of generating current. The open circuit voltage, V_{oc} , is the maximum voltage available from a junction solar cell, and it occurs at zero currents. The V_{oc} values were obtained from the intersection of the $I-V$ curve and the horizontal axis voltages.

It is clear that the PIN solar cell offers a short circuit current of 31.55 mA/cm², an open circuit voltage of 0.74V, and a maximum power of 18.68mW / cm².

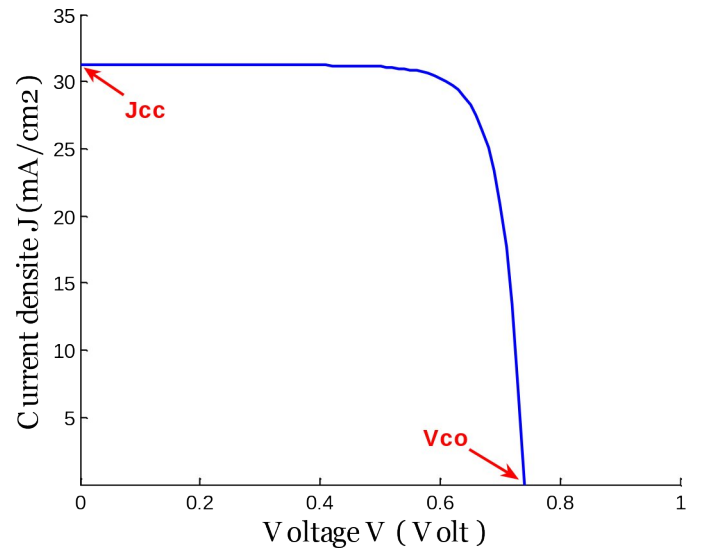


Fig. 4. Simulated current-voltage characteristic of the PIN solar cell.

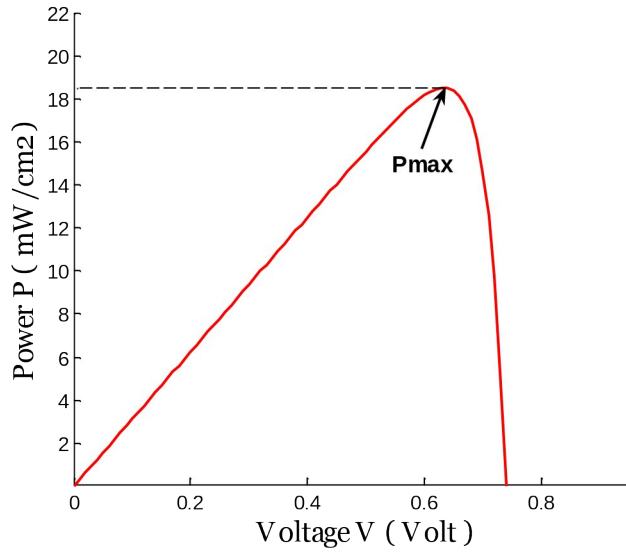


Fig.5. Simulated power-voltage characteristic of PIN solar cell.

B. Optimization of layer thickness

We varied the thickness W_i (μm) of the intrinsic layer of our model in an interval ranging from 0.5 to 6 μm , then we noted the different parameters of PIN cell.

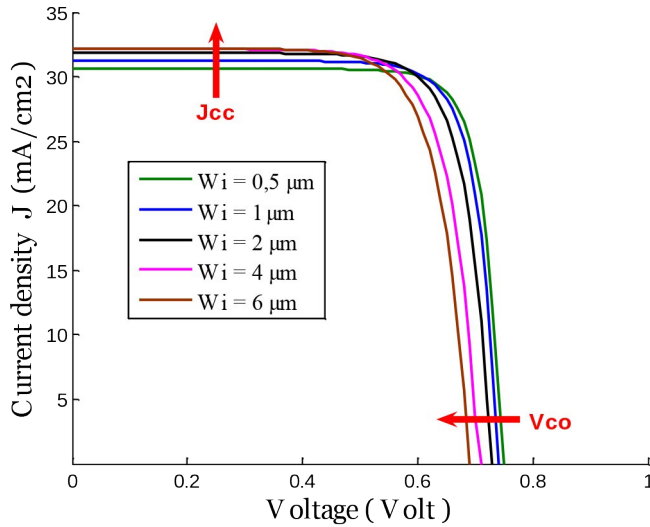


Fig.6. Current-voltage characteristics for different thicknesses of intrinsic layer

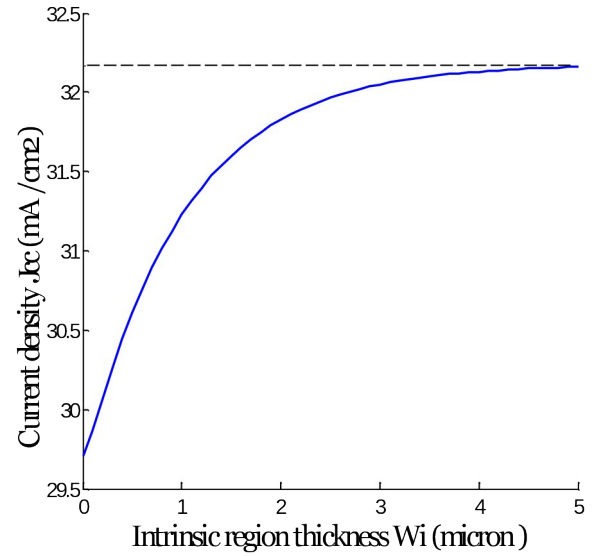


Fig. 7. Short-circuit current (J_{cc}) according to intrinsic layer thickness

Figures 6 and 7, shows that the short circuit current J_{cc} increases with the increase of i-layer thickness W_i , it reaches 32.17 mA/cm^2 . With an increase in i-layer thickness, the more photon energy will be absorbed and multiply the electron-hole pairs generation. On the contrary, the open circuit voltage decreases with the increase of i-layer thickness, since it depends on the geometry of the junction considered.

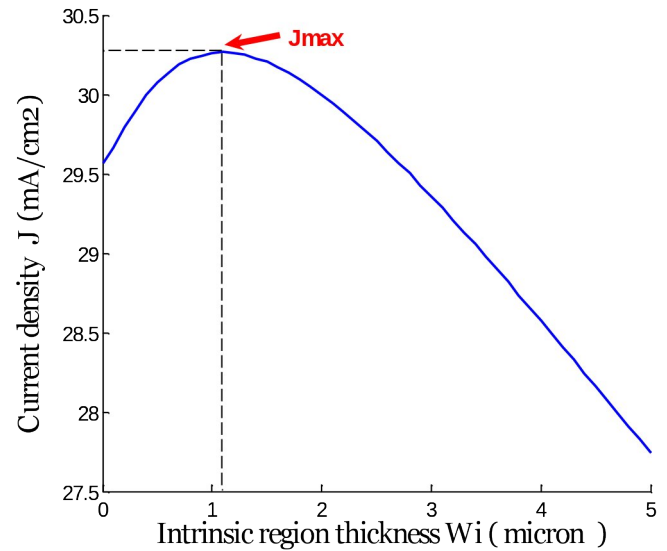


Fig. 8. Output current for different thicknesses of intrinsic layer

Figure 8 shows that as soon as an intrinsic layer of 0.5 μm is integrated, the current delivered by the

cell increases. The intrinsic layer extends the space charge zone of the cell and therefore increases photons absorption and collection speed of the photocurrent, therefore the delivered photocurrent density increase up to a maximum value of 30, 27 mA /cm² for W_i ranging from 0.75 μm to 1.5 μm then decreases for values greater than this thickness, due to the fact that the increase in the thickness of the intrinsic zone increases the possibility of photo carriers recombination.

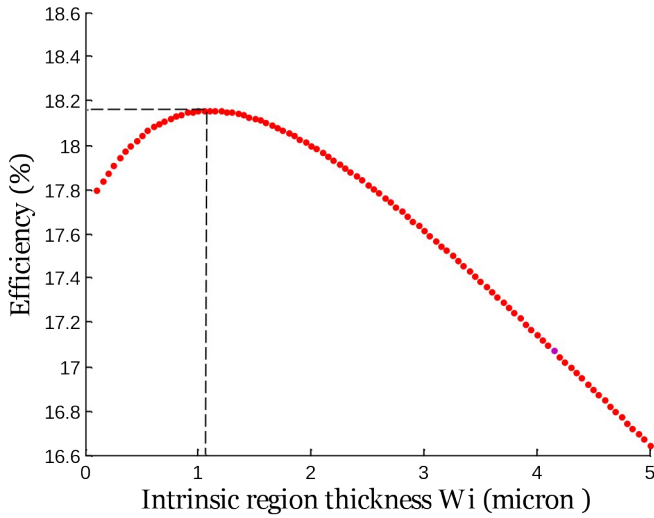


Fig.9. Cell efficiency according intrinsic layer thickness

Another key performance characteristic of a solar cell is the efficiency η , which is the ratio of maximum output power to the incident light power.

From figure 9, we notice that efficiency conversion varies with the thickness W_i . It reaches a maximum value of 18.16% for a thickness of $W_i = 1.1\mu\text{m}$. Above 1.1 μm the efficiency decreases. As thickness W_i increases, the electrons generated can recombine before reaching the contacts and so will not be collected, consequently the decrease in efficiency. From these key performance characteristic, we can understand that the optimized thickness of the i-layer is in the range around 0.75 to 1.5 μm . The quality of the i-layer is dependent also on the thickness.

IV. Conclusion

The numerical analysis of a-Si:H/a-SiC:H single-junction solar cell with i-layer used as the intermediate absorbing layer (a-Si:H) placed between layers of p-type (a-SiC:H) and n-type (a-Si:H) has been conducted. It is established that, after optimizing the solar cell parameters, its highest efficiency of 18.16% is achieved at 1.1 μm thickness of i-layer. The maximum experimental value of the similar solar cell efficiency is 10.1% [12].

For a thinner thickness of the i-layer, the solar cells could not effectively absorb all of the sunlight. Therefore, the short circuit current and the output power would be low. In addition, many point defects are generated in the sample with a thicker layer and the recombination phenomena are greater, which weakens the photo-generated current.

The cell conversion efficiency can be much improved compared to a single PIN junction structure if two or more PIN structure diodes with preferably different optical gaps are stacked on top of each other.

The focus on manufacturing solar cells is not sufficient for the overall performance improvement. Another important aspect to study rigorously is the phenomenon of degradation induced by light observed in cells based on a-Si:H.

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