THEORETICAL PERFORMANCE OF A MULTILAYER SILICON SOLAR CELL

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Abstract
We conceived a model of multilayer silicon solar cell were the light penetrates the cell perpendicularly to the junctions. The contacts connect the n-layers together and the p-layers together. The simulation of the current under AM0 indicates that the short-circuit current in this kind of structure is 1.35 higher than the classical p-n junction.

In this article we simulate the I-V characteristic with different layers resistance, we simulate also the output power versus the series resistance. The preliminary results of the simulation indicate that the bulk layers resistances have more effect on the reduction of the open circuit voltage and the output power than the frontal resistance. Our goal is to optimize the thicknesses of the layers for a fixed resistivity and to predict the efficiency for a given geometrical configuration.

Keywords
Solar cell, modeling, simulation, multilayer

Introduction
Since the efficiency is an important economical factor in photovoltaic (PV) arrays [1], making higher efficiency silicon solar cells – at no higher cell cost – is an important way of making energy conversion by solar cells more competitive. Silicon is the most abundant element in the earth crust and is keeping up with other PV materials: the efficiency of silicon solar cells increases steadily year after year [2, 3, 4, 5, 6]. The enhancement of the silicon solar cell efficiency is obtained due to the researchers' ability to minimize the optical losses and the bulk and surface recombination effects on the collection.

The Series Resistance
In a real simple n-p solar cell the current-voltage equation is:

\[ I = I_L - I_0 (\exp[\frac{V + R_s I}{R_{th}}] - 1) - \frac{V + R_s I}{R_{th}}, \]  

(1)

where \( R_s \) and \( R_{th} \) are respectively the series and shunt resistance. The series resistance \( R_s \) of a solar cell is the sum of the frontal contact resistance, the back contact resistance and the bulk resistance.

To increase the output voltage and the fill factor one should decrease the voltage drop due to the series resistance \( R_s \) of the cell. The resistance of the n frontal layer is important since the electrons travel across this layer from their birthplace to the grid finger. This bulk resistance virtually equals:

\[ R = \rho \frac{x}{A}, \]

where \( \rho \) is the bulk resistivity, \( x \) is the length of the path of the current through the emitter, and \( A \) is the cross section perpendicular to the current flow, defined as the product of the thickness by the length of the grid finger (Figure 1).
For a 1cm x 1cm cell the area of the emitter \( A \) equals \( t \). The thickness \( t \) is very small compared to the length of the path. The resistance increases when \( t \) decreases; it may reach high values altering the \( I-V \) characteristic.

The voltage drop missing at the output of the solar cell is subtracted from the voltage in the \( I-V \) characteristic as follows:

\[
J = J_o - \frac{i_o}{L} \left[ \exp(\alpha V + \beta J \times L^2) - 1 \right]
\]

where \( J \) is the current density under the voltage \( V \), \( J_o \) is the photocurrent density (i.e. the short-circuit current), \( i_o \) is the saturation current, \( \alpha = \frac{q}{kT} \) and \( \beta = \frac{\alpha}{2t} \) where \( \rho \) is the resistivity of the emitter and \( t \) its thickness.

The output power per unit area is given by an implicit function with respect to \( J \) and \( V \):

\[
P = J \times V = J_o \times V - \frac{i_o \times V \times \exp(\alpha V + \beta J \times L^2)}{L} - 1
\]

The maximum power and the fill factor were computed in a previous work [7] for a simple p-n solar cell as a function of the emitter resistivity, the emitter thickness and the frontal contact fingers spacing. In such a geometrical configuration we can consider the emitter resistance \( R = J L^2 \).

**Maximizing the Current**

Multilayer structure increases the space charge region by creating many junctions in the path of the light, so the electron-hole pairs are always created near a junction. This may be obtained by creating many successive layers with opposite conductivity, i.e. p-n-p-n. At the frontier between two opposite layers there are an abrupt p-n junction and a space charge region. The minority carriers have then less time to recombine before they meet the electric field of the space charge region, and are swept to the side where they are majority carriers, where they carry the current towards the contact.

Such a structure is represented in Figure 2. It consists of four-layer p-n-p-n, where the n regions are shallow. The contacts are taken laterally on the edge of the layers to allow the collection from the different layers.

**Figure (1):** Schematic diagram of the ideal p-n silicon solar cell used in the model. The bold arrow indicates a current path.
These contacts may be semiconductor pipes [8] or buried contacts [9]. The series resistances of the layers are represented in Figure 3 on the equivalent circuit.

In this cell the light enters through the p+ face along the x-axis. The minority carriers flow through the junction longitudinally along the x-axis too but the majority carriers current flow transversally from their birthplace towards the contacts, each type of carriers flows in one direction as shown by the thick arrows on Figure (2) the electrons flow in the n layers towards the negative contact and the holes flow in the p-layer towards the positive contact. The band structure diagram of multi-layer silicon solar cell is shown in Figure (4).
The short-circuit current of a five-layer structure was computed in a previous work [10] and the comparison to a classical p-n junction short-circuit current gave Figure (5). A four-layer stack with floating junction has been already made by M. Green et al. and gave an efficiency of 17.6% [9]. Our four-layer model is different and needs special care since the currents from each layer are not equal and so is the voltage drop due to the series resistance.

The Current-voltage Characteristic Simulation

We simulated the current voltage characteristic of the circuit shown in Figure 3. The photocurrents in the three current generators are estimated from our previous work [10]. These currents are, respectively, 23 mA, 15 mA and 10 mA at the frontal, medium and third junction. This gives a total short-circuit current of 48 mA. The saturation current is taken the same for the three junctions, i.e. 10-12 A. As a first estimate we consider that each layer has a lump resistance. All the resistances are taken equal, except for the frontal layer. This allows us to take into account that the frontal layer is usually made thinner to avoid the maximum surface recombination velocity effect.
The simulation is conducted as follows:
1- the voltage at the ends of each diode is given by:
\[ V = \frac{kT}{q} \log\left(\frac{i}{i_0} + 1\right) \tag{4} \]
where the letters indicate their habitual meaning.
2- the voltage \( V \) is calculated using three different paths, which gives three different independent equations. The currents in the diodes are respectively \( i_{d1} \), \( i_{d2} \) and \( i_{d3} \). The voltage across the circuit is:
\[ V_1 = \frac{kT}{q} \log\left(\frac{i_{d1}}{i_0} + 1\right) - R \times (.023+.015) - R \times (.023- i_d1) \tag{5} \]
\[ V_2 = \frac{kT}{q} \log\left(\frac{i_{d2}}{i_0} + 1\right) - R \times (.023+.015) - R \times (.015+.010 - i_{d2}-i_{d3}) \tag{6} \]
\[ V_3 = \frac{kT}{q} \log\left(\frac{i_{d3}}{i_0} + 1\right) - R \times (.010+.015 - i_{d2}-i_{d3}) - R \times .010 \tag{7} \]
3- by varying the current in each diode, we compare the voltages until we obtain almost the same voltage across the three paths. The output voltage \( V \) of the multilayer cell is taken as the average of the three voltages. The current is the total photocurrent (48 mA in our case) minus the currents across the diodes.
We used MATLAB software to process these computations. The results are shown in Figures 6, 7, 8 and 9 below. Only the lump resistance \( R_1 \) (for the front layer) and \( R \) (for each of the three bulk layers) varies from one figure to the other. On each figure below we report the I-V characteristic and the output power. Each curve is carried out for a given couple of resistances \((R_1,R)\).

**Summary and Conclusion**
The results of the simulation show that the output power is less sensitive to the frontal layer resistance. In the case of a bulk layers resistance of \(10^{-4} \Omega\), the frontal layer resistance has no effect at all if it is taken less than 0.1 \( \Omega \) and the current is the same as if \( R_1 = 10^{-4} \Omega \) (Figure 6).

![Figure (6):](image.png)
The simulated I-V characteristic (C) and output power (P). In this figure the bulk resistance is the same (\( R = 10^{-4} \Omega \)), the frontal layer resistance is \(10^{-4} \), 1, 3, 5, 7 and 10 \( \Omega \) respectively from the highest to the lowest efficiency.
As expected, the open circuit voltage and the fill factor are sensitive to the series resistance. The open circuit voltage decreases with increasing bulk layers resistance as shown in figure 8, but it is less sensitive to the frontal resistance as shown in Figure (7). The maximum output power and the fill factor are also more sensitive to the bulk layers resistance than to the frontal layer resistance as shown in Figure (7).

**Figure (7):**
The simulated I-V characteristic (C) and output power (P) for the following couples of resistances (R1, R) expressed in Ω, 1: (0.001, 0.001), 2: (8, 0.001), 3: (0.1, 0.1) and 4: (8, 0.1) respectively from the highest to the lowest power. These values are to be compared of the values of figure 8. The open circuit voltage is less sensitive to the frontal layer resistance.

**Figure (8):**
The simulated I-V characteristic (C) and output power (P) for the following couples of (R1, R), 1: (0.01, 0.001), 2: (1, 0.01), 3: (0.01, 1) and 4: (1, 1) respectively from the highest to the lowest power. These values are to be compared of the values of figure 7. The open circuit voltage is more sensitive to the bulk layers resistance.
We also simulated on the same scale the output voltage of a classical p-n cell to compare it with the multi-layer cell. Figure 9 shows this comparison. The resistance value used is high for both, i.e., 1 Ω. The short-circuit current was taken according to ref [10], i.e., 48 mA/cm² for the multilayer cell and 35.5 mA/cm² for the monojunction cell. We remark that the open circuit voltage of the monojunction is higher but its maximum output is lower, which justify the utility of the model. As far as the maximum output power is concerned, what we loose in the voltage through the series resistance in the multi-layer cell is less than what we gain in the current compared to the classical cell even if the series resistance is very high.

The simulation of the I-V characteristic and output power of a multi-layer solar cell shows that the enhancement of the short-circuit current obtained in the multilayer case compared to the classical p-n junction is not lost through the series resistance, especially in the case of a low bulk resistance, even if the frontal layer resistance is high.

Computations are carried out to integrate this calculation into a more complete model where variable geometrical dimensions are taken into account under AM 1.5 illumination.

References