

## Simulation photoelectric parameters of vertical junction solar cells



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### ABSTRACT

Many properties of the solar cells are being studied extensively. In this study, the basic photoelectric parameters of vertical junction solar cell were modeled. Attempts were made to approach the scientific work both physically and programmatically. In terms of programming, a perfect algorithm has been developed for modeling vertical junction solar cell in the Sentaurus TCAD software package. Using this algorithm, a vertical junction solar cell was modeled. The main focus was on the comparison of the photoelectric parameters of a vertical junction solar cell consisting of 3 elements with the photoelectric parameters of a vertical solar cell consisting of single element. The results obtained were physically based.

**Key words:** Vertical junction solar cell, p-n junction, simulation, Sentaurus TCAD

### 1. INTRODUCTION

The most widely used renewable energy source is solar energy [1]. There are two different ways to use solar energy. The first is to convert solar energy into heat energy. The second is to convert light energy into electricity. It is impossible to imagine today without electricity [2]. A photovoltaic device that converts light energy into electricity is called a solar cell. There are many types of solar cells. About 95% of the solar cells currently produced are silicon-based solar cells [3]. The efficiency of a simple silicon-based solar cell does not exceed 29% [4-7]. Tandem solar cells were developed using a variety of bandgap. In our previous work, the effect of nanoparticles on the photoelectric parameters of solar cells was studied [8-9].

Concentration and use of light are becoming more popular. Vertical junction solar cells have also been developed to receive energy from the area occupied by the front contact and the rear contact. Its advantage is that it reduces contact resistance. It also reduces the shadow effect. As the intensity of light increases, so does their efficiency. Numerous scientific studies have studied the dependence of the efficiency of vertical junction solar cells on the intensity of light. In our research, we modeled vertical junction solar cells in Synopsys program of Sentaurus TCAD software package.

By modeling solar cells, we can find the optimal option between dimensions and materials. This saves time and money on experimentation. Today, in each field, simulation is becoming a separate area of hunting modeling. Sentaurus, Lumerical, Silvaco, Comsol, Crosslight, and Cogenda software packages are widely used to simulate physical processes [11-13].

### 2. METHOD

We use Synopsys company product of Sentaurus TCAD software package to model solar cells. This is because the results obtained from the solar cell modeled in this program are very close to the results obtained in real experience. This section provides information on the model of the solar cell created in Sentaurus TCAD.

#### 2.1 Geometrical model

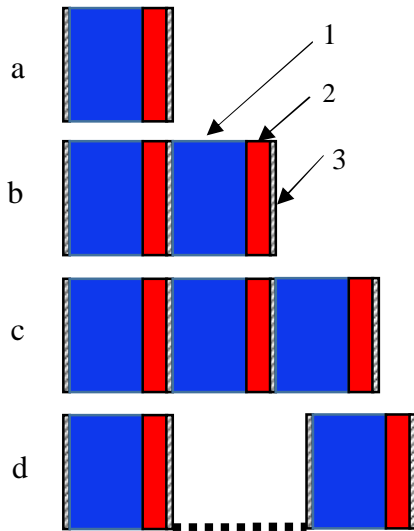
We use the Structure Device Editor to create a geometric model. In SDE, mostly geometric structures are created by writing code in the Tool Command Language. A perfect algorithm for a vertical junction solar cell has been developed. With this algorithm we can create an arbitrary number of vertical junction solar cells. Another advantage is that the following quantities are taken as variables [18]:

1. The widths of the p and n layers
2. Thickness of solar cell
3. Doping concentration

```
(do ((i 0 (+ i 1)))
  ( (= i @n@)
    (begin
      (set a (* i (+ dn dp)))
      (element a (string-append "p_soxa." (number->string i))
        (string-append "n_soxa." (number->string i)))
      (if (> i 1)
        (begin
          (sdegeo:create-rectangle (position (- a dm) 0 0)
            (position (- a dm) 0 0) "@material@" (string-append
              "metall." (number->string i)))
          )
        )
      )
    )
  )
)
```

In the construction of the algorithm, a single solar cell was created through the first procedure. Then, n solar elements were connected vertically in series through the loop. Each element was connected by a metal contact.

```
(define element
  (lambda(x1 name1 name2)
    (sdegeo:create-rectangle (position x1 0 0) (position (+
x1 dp) L 0) "Silicon" name1)
    (sdegeo:create-rectangle (position (+ x1 dp) 0 0)
(position (+ x1 dp dn) L 0) "Silicon" name2)
  )
)
```



**Figure 1.** Silicon based vertical junction solar cell. 1 – p layer, 2 – n layer, 3 – metal contact, a – one vertical junction solar cell, b – two vertical junction solar cells, c – three vertical junctions solar cell, d – n vertical junction solar cells

## 2.2 Theory

The Sentaurus software package is based on a numerical method, but it contains a database of experimental results for each substance. Once we have published the material via SDE, we need to add this material into the Sentaurus Device settings [18]. There are two ways to add parameters to a model. The first is by writing to the parameter file only the desired properties of the material through the functions. The second is by specifying the location of the required database in the parameter file. We used the second method in our model. Because the computation for the semiconductor device we made is perfect and complex. The execution and management of the computational work is done directly by writing code in TCL to the command file of the Sentaurus Device. The command file of the Sentaurus device consists of 5 main functions. These are File, Electrodes, Physics, Plot, CurrentPlot, Math and Solve. Entering the wrong command in any of these functions will result in an incorrect result. Since this article is mainly about the models of vertical junction solar cells and the results obtained in them, we will not dwell on the commands in each function. This section

only describes the commands used in the Physics function and their physical basis.

A two-dimensional model has been developed to ensure symmetry in the solar cell and to make calculations faster. We also included the Areafactor because a lot of physical quantities depend on size. If we take the value of the Areafactor as 1e11, then we get the width of the solar cell as 1 μm.

The concentration of charge carriers in semiconductors is determined by Fermi statistics. Because electrons belong to the family of fermions. We also used Fermi statistics to determine the amount of charge carriers in a solar cell (Formula 1). To do this, we entered the Fermi keyword into the Physics function. If we do not enter this keyword, Sentaurus will automatically select the Boltzmann statistic. We know that the accuracy of Fermi statistics is higher than Boltzmann statistics.

$$\begin{aligned} n &= N_c F_{1/2} \left( \frac{E_{F,n} - E_c}{kT} \right) \\ p &= N_v F_{1/2} \left( \frac{E_v - E_{F,p}}{kT} \right) \end{aligned} \quad (1)$$

Here: n – electron concentration, p – holes concentration,  $F_{1/2}$  – Fermi integral,  $E_c$  – conduction band energy,  $E_v$  – valence band energy,  $E_{F,n}$  – quasi fermi energy for electrons,  $E_{F,p}$  – quasi fermi energy for holes, T – temperature,  $N_c$  – density of states in conduction band,  $N_v$  – density of states in valence band, k – Boltzmann constant.

Shockley-Read-Hall (SRH) and Auger recombination form the main part of recombination in silicon-based solar cells. Radiation recombination is also present but its share is very small. So we didn't use it in the simulation. The keyword Recombination (SRH Auger) was used to add recombination to the model.

Because we use Fermi statistics, pure SRH is used in the model (Formula 2) to calculate the recombination rate. SRH recombination occurs due to defects. That is, each defect in the crystal creates a certain energy level in the forbidden zone [14].

$$R_{net}^{SRH} = \frac{np - \gamma_n \gamma_p n_{i,eff}^2}{\tau_p (n + \gamma_n n_1) + \tau_n (p + \gamma_p p_1)} \quad (2)$$

Here:  $\gamma_n, \gamma_p$  – coefficients,  $\tau_n, \tau_p$  – electron and holes lifetimes,  $n_1, p_1$  – electron and holes concentration in trap.

Auger recombination is more common in areas with high input concentrations. Because it is a 3-particle recombination. It is mostly in the emitter area of the solar cell. Calculated using the pure Auger recombination rate (Formula 3).

$$R_{net}^A = (C_n n + C_p p) (np - n_{i,eff}^2) \quad (3)$$

Here:  $C_n, C_p$  – auger constants.  $n_{i,eff}$  – effective intrinsic carrier concentration

The keyword *Mobility (DopingDependence)* is used in this model to calculate the mobility of the charge carriers. We did not select a specific model for mobility during the simulation. The solar element is silicon based. Therefore, the Masetti model in the Sentaurus Device is automatically selected for mobility. In the Masetti model, mobility is calculated using (Formula 4).

$$\mu_{dop} = \mu_{min} \exp\left(-\frac{P_c}{N_{A,0} + N_{D,0}}\right) + \frac{\mu_{const} - \mu_{min2}}{1 + \left(\frac{N_{A,0} + N_{D,0}}{C_r}\right)^\alpha} - \frac{\mu_1}{1 + \left(C_s / (N_{A,0} + N_{D,0})\right)^\beta} \quad (4)$$

Here:  $\mu_{min}$ ,  $\mu_{min2}$ ,  $\mu_1$  – material type dependent constants,  $P_c$ ,  $C_r$ ,  $C_s$  – doping concentration dependent constant,  $\alpha, \beta$  – fitting parameters,  $\mu_{const}$  – temperature and phonon scattering dependence mobility,  $N_{A,0}$ ,  $N_{D,0}$  – acceptor and donor concentration.

The absorption coefficient of light is a quantity that depends on the wavelength of light. For example, silicon absorbs light in the visible spectrum. This means that the silicon solar cell also absorbs most of the light in the visible field. To determine the optical properties of the solar cell, we used the Transfer Matrix Method (TMM) in the model. TMM is based on Fresnel and Burger-Lambert laws. Fresnel's laws determine the return and transmission of light on the surface. The Burger-Lambert law calculates the absorption of light in a layer. TMM is used to determine the optical properties of a multilayer system (Formula 4) [16].

$$\begin{bmatrix} E_i \\ E_r \end{bmatrix} = M \begin{bmatrix} E_t \\ 0 \end{bmatrix} \quad (4)$$

Here:  $E_i$  – electric field of incident light,  $E_r$  – electric field of reflection light,  $E_t$  – electric field of transmission light,  $M$  – transfer matrix.

At least the electrostatic potential must be considered in the modeling of each electrical device. The electrostatic potential is determined by solving the Poisson equation by the charge density. To solve the Poisson equation, wrote the keyword "Poisson". In the general case, the Poisson equation is as follows (Formula 5). It varies depending on the physical properties of the model.

$$\Delta\phi = -\frac{q}{\epsilon} (p - n + N_D + N_A) \quad (5)$$

Here:  $\epsilon$  – dielectric permittivity,  $N_D$  va  $N_A$  – donor and acceptor concentration,  $q$  – charge.

### 3. RESULTS

Basic photoelectric parameters were determined by modeling vertical junction solar cells. The model modeled vertical junction solar cells consisting of two simple single and three solar elements.

A 15-nm-thick silicon-based solar cell was modeled. Copper was used to connect each element vertically with each other. The current density distribution in a single solar cell is shown in Figure 2. The current-density distribution in a matrix consisting of 3 vertical junction solar cells is shown in Figure 3.

The width of the base was 20  $\mu\text{m}$  and the width of the emitter was 5  $\mu\text{m}$ . The input concentration is  $1e17$  for type n and  $1e15$  for type p. Phosphorus atoms were introduced as type n and boron atoms as type p.

The current densities of a single and 3-layer vertical junction solar cell have an average value of  $1e-3 \text{ A/cm}^2$ . Since the

main charge junctions and the separation of the electron cavities are in the p-n junction, the value of the current density is higher in this area. The current density is higher at the central contacts of multilayer solar cells.

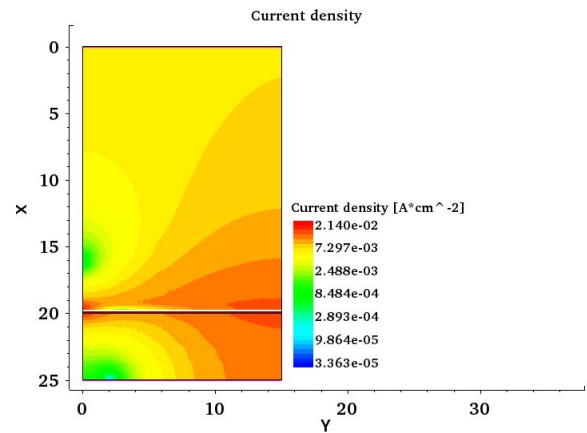


Figure 2. Current density distribution in a single solar cell

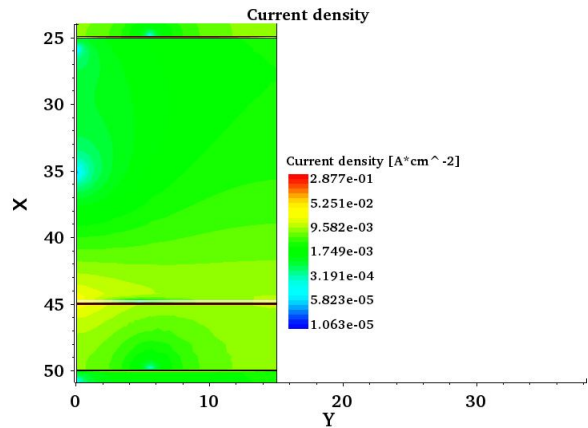


Figure 3. The current density distribution in the solar cell in the center of a vertical junction matrix consisting of 3 solar cells

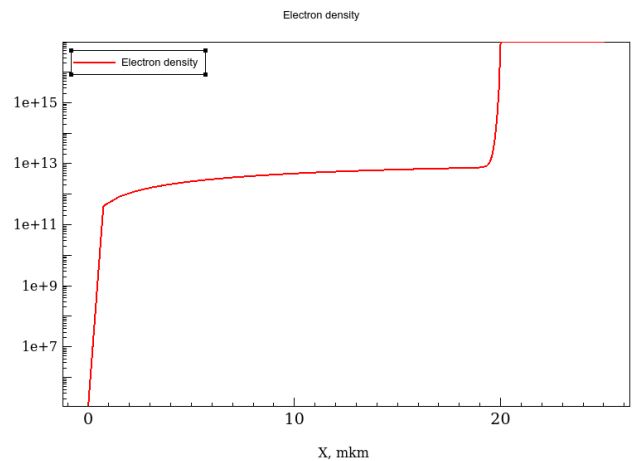
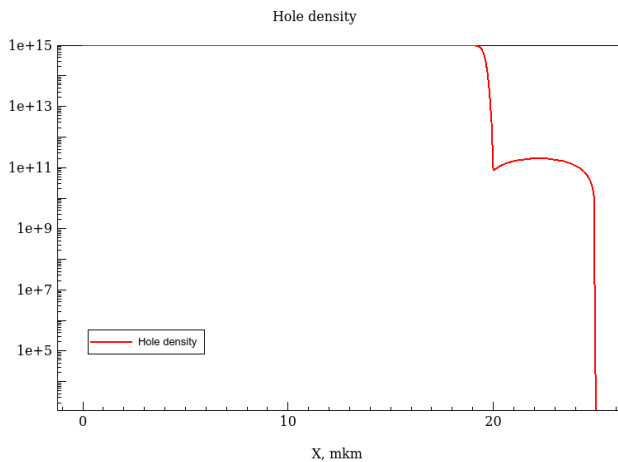
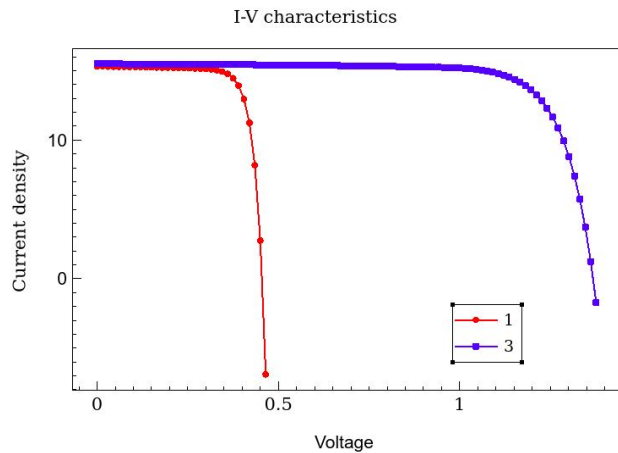


Figure 4. Longitudinal distribution of the concentration of electrons in a vertically illuminated solar cell relative to the p-n junction

We know that electrons and cavities are formed by many events. For example, optical generation and thermal generation. In addition, their concentration decreases due to recombination. Given these phenomena, the distribution of concentrations of total electrons (Fig. 4) and cavities (Fig. 5) was determined. These graphs show that the p area is 0 to 20  $\mu\text{m}$  and the n area is 20 to 25  $\mu\text{m}$ . In the P field, the average concentration of the main charge carriers, holes, is  $1\text{e}15\text{ cm}^{-3}$ . That is, we are equal to the concentration of the input. Because each boron atom forms a hole when it is inserted into silicon. The electron concentration of the major charge carriers in the N field is also equal to the donor input concentration. The average concentration of non-basic charge carriers in the P region, electrons, is  $5\text{e}13\text{ cm}^{-3}$ . The concentration of non-basic charge carriers in the N field is  $5\text{e}11\text{ cm}^{-3}$ .



**Figure 5.** Longitudinal distribution of the concentration of holes in a vertically illuminated solar cell relative to the p-n junction



**Figure 6.** I-V characteristics of solar cells. 1- single vertical junction solar cell 3 – vertical junction solar cells with 3 elements

We can see that the volt-ampere characteristic of a vertical-junction solar cell depends on the number of elements (Figure 6). The developed model showed that if the number of elements in a vertical junction solar cell is even, then the output current is low, if it is odd, it is high.

#### 4. DISCUSSION

During the modeling of solar cells, only numerical methods and experimental results were relied upon. If we analyze the obtained results, we can see that they are close to the experimental results. We can determine the basic photoelectric parameters through the volt-ampere characteristic.

It is the simplest volt-ampere characteristic for solar cells (Formula 6).

$$I = I_{ph} - I_0 \left( \exp \left( \frac{qV + IR_s}{nkT} \right) - 1 \right) \quad (6)$$

Here: V- voltage, I – current,  $I_{ph}$  – photocurrent,  $I_0$  – dark current,  $R_s$  – series resistance, n – ideality factor.

We used the AM1.5 standards as the light source in the model. The short circuit current depends on the wavelength. To find the total short-circuit current, we integrate it from 0 to 10 as a function of wavelength (Formula 7). The AM1.5 spectrum is the closest light spectrum to the light spectrum. When we say that the wavelength is discrete, we determine the short-circuit current at each wavelength and add it to determine the total short-circuit current. The short-circuit current of 1 vertical junction solar cell is  $15.31\text{ mA/cm}^2$ . The short-circuit current of 3 vertical junction solar cells is  $15.5\text{ mA/cm}^2$ .

$$I_{sc} = \int_0^{\lambda_0} I_{sc}(\lambda) d\lambda \quad (7)$$

Here:  $\lambda$  – wavelength,  $I_{sc}$  – short circuit current

Given that each wavelength of light has a specific energy in the spectrum, we can find the number of photons at each wavelength. We can also determine the number of photons in the spectrum by summing them (Formula 8). The total number of photons in the AM1.5 spectrum is about  $1\text{e}17\text{ 1/cm}^2$ .

$$N_0 = \int_0^{\lambda_0} N(\lambda) d\lambda \quad (8)$$

$$n_A = \frac{1}{N_0} \int_0^{\lambda_0} N(\lambda) (1 - \exp[-a(\lambda)h]) d\lambda \quad (9)$$

$$I_{sc} = (W_1 + W_2) \eta_{coll} \eta_A q N_0 \quad (10)$$

Here:  $N_0$  – total photons number,  $N(\lambda)$  – the number of photons of a specific  $\lambda$  wavelength, h – thickness,  $W_1$  – n layer width,  $W_2$  – p layer width,  $a(\lambda)$  – the light absorption coefficient of the material depending on the wavelength,  $\eta_{coll}$  – collection factor,  $\eta_A$  – photon absorption factor.

The magnitude of the operating voltage depends on the short-circuit current and the reverse current (Formula 11). The reverse current is directly proportional to the square of the concentration of specific charge carriers. The salinity of a normal vertical junction solar cell is 0.465 V, the salinity of 3 vertical junction solar cells is 1.38 V.

$$V_{oc} = \frac{kT}{q} \ln \left( \frac{I_{sc}}{I_0} \right) \quad (11)$$

Maximum power is easy to determine in practice. There is also a theoretical calculation from a simple diode equation. By solving (Formula 13) we can calculate the maximum current and voltage. The main photoelectric parameters determined by the results obtained in the model are given in Table 1.

**Table 1.** Basic photoelectric parameters

Number of cells	Voc, V	Jsc, mA/sm <sup>2</sup>	Vmpp, V	Jmpp, mA/sm <sup>2</sup>	Pmpp, mW/sm <sup>2</sup>	FF
1	0.465	15.3	0.39	13.9	5.43	0.763
3	1.38	15.5	1.15	14.38	16.65	0.774

$$X_0 = \frac{q}{kT} V_0 \quad (12)$$

$$X + \ln(1 + X) = X_0 \quad (13)$$

$$I_m = I_{sc} - I_0 \exp[X_m] \quad (14)$$

$$P_m = I_m V_m \quad (15)$$

Here:  $I_m$  – maximum current on maximum power point,  $P_m$  – maximum power,  $V_m$  – maximum voltage on maximum power point,  $X$  – variable of equation.

**5. CONCLUSION**

This paper analyzes the results obtained by modeling vertical junction solar cells. It also provides information on the modeling sequence. We summarized the results as follows:

1. Care should be taken in choosing the number of vertically junction solar cells. Useful if the number of elements is odd.
2. It was found that the results obtained in the model were close to the results of previous experiments.
3. The results proved to be close to the theory as well. Theoretically, the results obtained through mathematical modeling were stated. Simulation is the process of solving a physical process using numerical methods in an algorithmic way using an electronic computer.
4. It has been found that vertical junction solar cells can be made in two different ways. That is, by creating a tunnel junction between silicon-based solar cells and metal contacts between the elements. We present in this article mainly the results of solar elements formed by metal contact between.

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